Techno-economic and sustainability models for integration of cassava waste-based biorefineries into cassava starch processes based on process simulation and a systems modelling approach

by

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Dissertation presented for the Degree

of

DOCTOR OF PHILOSOPHY
(CHEMICAL ENGINEERING)

in the Faculty of Engineering
at Stellenbosch University

The financial assistance of the National Research Foundation (NRF) towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at, are those of the author and are not necessarily to be attributed to the NRF.

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March 2021

Declaration

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This dissertation includes 4 original papers published in peer-reviewed journals or books and 1 unpublished publications. The development and writing of the papers (published and unpublished) were the principal responsibility of myself and, for each of the cases where this is not the case, a declaration is included in the dissertation indicating the nature and extent of the contributions of co-authors.

Date: *March 2021*

Abstract

Cassava crop high starch yields, accompanied by its tolerance to drought/low soil nutrients, have increased research attention towards the crop's adoption as a potential food security and economic empowerment crop for South Africa. Widely consumed as food and livestock feed, cassava starch also has potential industrial applications in pharmaceuticals, specialty chemicals (e.g. succinic acid), ethanol, adhesive, and food derivatives (e.g. glucose syrup). Commercialization of industrial cassava starch facilities (CSF) depends on profitability and sustainable energy supply for operations. Residues generated by CSFs [cassava starch wastewater (CWW), bagasse (CB)], and cassava stalks (CS) could generate the requisite energy for cassava starch industries (CSI), thus there is potential to integrate waste-based bioenergy developments with CSFs. Cassava waste biorefineries (CWBs) for co-producing energy and high-value bio-products have been proposed as potential solutions to energy and cost limitations in CSFs. Attributed to knowledge gaps on the techno-economic feasibility (TEF) and long-term sustainability (economic + environmental + social) of such CWBs, conventional waste management schemes involve the burning of CS and anaerobic digestion of CWW & CB to produce biogas for starch drying heat, with the digestate being disposed into watercourses. This research, through Aspen Plus® process/economic modelling and SimaPro simulation, investigated the TEF and sustainability of CWBs in the South African socio-economic context, with an overall objective of contributing to knowledge towards the commercialization of CWBs. The investigated CWB scenarios include: (i) enhanced waste resource recoveries (energy, biofertilizer, water) through integrating CS into CSF waste treatment, and (ii) advanced CWBs [(I) combined heat & power, with (II) hexose-bioethanol, (III) pentose & hexose-bioethanol, (IV) pentose-bioethanol + glucose syrup, and (V) pentose-bioethanol + succinic acid)]. The results showed that combined treatment of CS (14.32 t/h) with CSF wastes (7.29 t/h DM CB + 377.83 t/h CWW) could ensure further resource recoveries, including bioelectricity (up to 31.96 MW), liquid/solid biofertilizer, and usable water, with potential energy self-sufficiency and economic enhancements for CSIs. Co-conversion of 450.89 t/h CS and CSF waste could ensure sufficient energy supplies for both CWBs and CSFs, plus 300 MW electricity (I), or 287 MW + 1.48 t/h bioethanol (II), or 121 MW + 8.95 t/h bioethanol (III), or 164 MW + 5.72 t/h bioethanol + 9.29 t/h glucose syrup (IV), or 161 MW + 5.72 t/h bioethanol + 6.9 t/h succinic acid (V). However, only scenarios (I)-(II) demonstrated economic viability, while (III)-(V) favor environmental sustainability. Revitalizing the CSI's via integrations with the resource recovery schemes, where the recoveries are re-used in the CSFs and crop cultivations, could ensure viable circular economy strategies that may enhance sustainable industrial developments. Hence, integrating CSFs with resource recoveries or CHP (I) or CHP + hexose-bioethanol (II) represent viable strategies for the synergetic advancement of food-energy security and low-carbon economies.

Opsomming

Kassawagewas se hoë styselopbrengs, gepaardgaande met sy toleransie vir droogte/lae grondvoedingstowwe, het navorsingaandag op die gewas se aanneming as 'n potensiële voedselsekuriteit en ekonomiese bemagtigingsgewas vir Suid-Afrika, verhoog. Wyd verbruik as voedsel en veevoer, het kassawastysel ook potensiële industriële toepassings in farmaseutiese produkte, gespesialiseerde chemikalieë (bv. suksiensuur), etanol, kleefmiddel, en voedselderivate (bv. glukosestroop). Kommersialisering van industriële kassawastyselfasiliteite (CSF) is afhangend van winsgewendheid en volhoubare energietoevoer vir bedryf. Residu's gegenereer deur CSF'e (kassawastyselafvalwater (CWW), bagasse (CB)), en kassawastingels (CS) kan die nodige energie vir kassawastyselindustrië (CSI) genereer, daar is dus potensiaal om afval-gebaseerde bio-energie-ontwikkelinge met CSF'e te integreer. Kassawa afval-bioraffinaderye (CWB'e) vir koproduksie van energie en hoë-waarde bioprodukte is voorgestel as potensiële oplossings vir energie- en kostebeperkings in CSF'e. Toegeskryf aan kennisgapings van die tegno-ekonomiese uitvoerbaarheid (TEF) en lang-termyn volhoubaarheid (ekonomies + omgewing + sosiaal) van sulke CWB's, behels konvensionele afvalbeheerskemas die verbranding van CS en anaerobiese vertering van CWW en CB om biogas vir styseldrogingshitte te produseer, met die vaste afsaksel wat verwyder word in waterlope. Hierdie navorsing, deur Aspen Plus® proses/ekonomiese modellering en SimaPro simulasie, het die TEF en volhoubaarheid van CWB's in die Suid-Afrikaanse sosio-ekonomiese konteks ondersoek, met 'n algehele doel om tot die kennis van die kommersialisering van CWB's by te dra. Die CWB-scenario's wat ondersoek is behels: (i) versterkte afvalhulpbron se herwinning (energie, biokunsmis, water) deur CS in CFS-afvalbehandeling te integreer, en (ii) bevorderde CWB's [(I) gekombineerde hitte en krag, met (II) heksosebio-etanol, (III) pentose en heksosebio-etanol, (IV) pentosebio-etanol + glukosestroop, en (V) pentosebio-etanol + suksiensuur)]. Die resultate het gewys dat

gekombineerde behandeling van CS (14.32 t/h) met CFS-afval (7.29 t/h DM CB + 377.83 t/h CWW) verdere hulpbronherwinning kon verseker, insluitend bio-elektrisiteit (tot en met 31.96 MW), vloeistof/vastestof biokunsmis, en bruikbare water, met potensiële energieselfgenoegsaamheid en ekonomiese versterkings vir CSI'e. Ko-omsetting van 450.89 t/h CS en CFS-afval kan genoeg energietoevoer verseker vir beide CWB's en CSF'e, plus 300 MW elektrisiteit (I), of 287 MW + 1.48 t/h bio-etanol (II), of 121 MW + 8.95 t/h bio-etanol (III), of 164 MW + 5.72 t/h bio-etanol + 9.29 t/h glukosestroop (IV), of 161 MW + 5.72 t/h bio-etanol + 6.9 t/h suksiensuur (V). Slegs scenario's (I) tot (II) het ekonomiese lewensvatbaarheid getoon, terwyl (III) tot (V) ten gunste van omgewingsvolhoubaarheid was. Om nuwe lewe in die CSI's via integrasies met die hulpbronherwinningskemas, te blaas, waar die herwinning hergebruik word in die CSF'e en gewaskweking, kan lewensvatbare sirkulêre ekonomiese strategieë verseker wat volhoubare industriële ontwikkelinge versterk. Daarom, om CSF'e met hulpbronherwinning of CHP (I) of CHP + heksose-bio-etanol (II) te integreer, verteenwoordig lewensvatbare strategieë vir die sinergistiese bevordering van voedselsekuriteit en lae-koolstof ekonomieë.

Acknowledgments

The PhD journey, like any other adventurous endeavour, had its highs and lows. This PhD study could not have been successful without the following personalities/institutions:

- **Prof. Annie Chimphango**. Beside the remarkable academic support, I experienced your supervisory role from three dimensions- a steadfast mentor, a wholehearted mother, and a reliable friend, which inspired me to the end. May the lessons of inspiration guide my dealings with others.
- **Prof. Anthony Roskilly & Dr. Janie Ling-Chin** (Durham Energy Institute, Durham University, UK). Appreciations for the valuable orientation and supervision that contributed to the success of the study.
- **The Bioresource Engineering Research group**. Thanks for the collective passion to change the narrative from ‘biomass wastes’ to ‘biomass resources’, the intellectual discussions, and the encouragements during challenging times. Personally, you redefined ‘colleagues’.
- **National Research Foundation’s Southern African Systems Analysis Centre (NRF-SASAC, South Africa); British Council’s Newton Fund (South Africa); Process Engineering Department (Stellenbosch University)**. Appreciations for the financial supports, without which the research would have been a dream.
- **Prof. Patricia Thornley & Dr. Mirjam Roeder** (The Energy and Bioproducts Research Institute, Aston University, UK). Many thanks for the valuable introduction to life cycle simulations, and the ‘free lunch’ and ‘social lessons’ that came with it.
- **Mama Heide and Papa Ulli**. Your selfless parenting role was a real boost, but your collective advice that ‘PhD study should be regarded as service to humanity, and not just an academic activity’ gave life and purpose to the study.
- **Family & friends**. We run the race with a purpose- sacrificing our time and resources to contribute to the course of humanity. Share in the success!

Dedication

To God Almighty- the source of wisdom, strength and grace throughout this study; and Joseph and Jemima- my parents, who gave their all to make this feat possible.

"I will praise You, O Lord, with my whole heart; I will tell of all Your marvelous works."

Psalm 9:1

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List of Acronyms/Abbreviations

1-G First generation
2-G Second generation
AD Anaerobic digestion
BAU Business-as-usual
C5 Pentose sugars
C6 Hexose sugars
CAGR Compound annual growth rate
CB Cassava bagasse
CE Circular economy
CHP Combined heat and power
COD Chemical oxygen demands
CS Cassava stalks or stems
CSF Cassava starch facilities
CSI Cassava starch industries
CSL Corn steep liquor
CWB Cassava wastes biorefineries/bioenergy
CWW Cassava starch wastewater
DAP Diammonium phosphate
DM Dry mass
EH Enzymatic hydrolysis
eLCA Environmental Life Cycle Assessments
EtOH Ethanol
FCI Fixed capital investment
FEP Freshwater eutrophication potential
FETP Freshwater ecotoxicity potential
FGD Flue gas desulfurization
FRSP Fossil resource scarcity potential
GHG Greenhouse gases
GS Glucose syrup
GWP Global warming potential
IRR Internal rate of return
LCC Life Cycle Costing
LCSA Life Cycle Sustainability Assessments
MCA Multi-criteria analysis
MESP/MEP/MSP Minimum expected selling prices
NPV Net present value
POC Plant overhead cost
PSI Percentage sustainability index
RF Recoverability fraction
RO Reverse osmosis
RPR Residues-to-product ratio
SA Succinic acid
SDHA Starch drying hot air
SHF Separate hydrolysis and fermentation
sLCA Social Life Cycle Assessments
SM Systems modelling
SSF Simultaneous saccharification and fermentation
TAP Terrestrial acidification potential
TBL Triple bottom line (economic, environmental, social)
TCI Total capital investment
TDC Total direct cost
TEA Techno-economic assessments
TETP Terrestrial ecotoxicity potential
TFC Total fixed costs
TIC Total indirect costs
TOC Total operating cost
TPC Total production cost
TRR Total resource recovery
TS Total solids
TVC Total variable costs
WCF Waste conversion facility
WWT Wastewater treatment

List of key publications

Journal Papers

1. **Padi RK**, Chimphango A., 2020. Commercial viability of integrated waste treatment in cassava starch industries for targeted resource recoveries. J Clean Prod; 265: 121619 (Published online).
2. **Padi RK**, Chimphango A., 2020. Feasibility of commercial waste biorefineries for cassava starch industries: Techno-economic assessment. Bioresour Technol; 297: 122461 (Published online).
3. **Padi RK**, Chimphango A. Comparative sustainability assessments for integrated cassava starch wastes biorefineries, J Clean Prod; 125171 (Published online).

Book Chapter

Padi RK, Chimphango A., 2020. Postharvest technology for advancing sustainable bioenergy production for food processing and reduction of postharvest losses. In: Charis M. Galanakis, editor. Food losses, sustainable postharvest and food technology, Elsevier (In press).

Poster Presentation

Padi R.K., Chimphango A., Roskilly A.P. 2019. Sustainability of selected resource recoveries from integrated waste treatment in cassava starch industries. Presented at the IIASA' Systems Analysis and Africa conference (Transformative uses of systems analysis to address regional challenges), Johannesburg, South Africa. Abstract available at: https://iiasa.ac.at/web/home/about/regional/africa/South_Africa_conference_program_Final.pdf.

1 Introduction

1.1 Background

Global food security remains unrealized due to diverse constraints, such as increasing global population, rising scarcity of agriculture resources (e.g. arable lands), and unfavorable climatological variables (e.g. drought). It is estimated that nearly 11% of the global population (815 million people) are malnourished, with high severity in developing regions [1]. For instance, for the year 2017, estimations showed that percentages of the populations that were undernourished in the developed regions of Northern America or Europe were below 2.5%, while those for developing regions of Africa, Asia, and Latin America/Caribbean were 20.4%, 11.4%, and 6.1% respectively [1]. Susceptibility of agriculture productivity to frequent droughts, particularly for the rain-fed agriculture prevalent in sub-Saharan Africa (SSA) (~95% of farms), results in low food production, which contributes to the high incidence of food insecurity [1–3].

Similarly, in South Africa, reports suggest that from 2010 to 2012, nearly 28.6% of the estimated population (52.83 million at an annual growth rate of 1.34%) lacked access to adequate food [4]. The arable land area is said to be declining over the years [5]. Intense drought contributed to the failure of over 34% of farming lands since the 1990's, with most of these lost lands transformed to other uses such as human settlements [6]. Intensive farming, characterized by thorough inputs of energy, irrigation, mechanization, fertilizer, pesticides, and genetically improved cultivars, has subsequently been considered to meet the rising food demands by the growing population [6]. However, associated drawbacks of high economic, environmental, and natural resource burdens undermine the benefits of high food production. For example, applied fertilizers washed-off by rain or irrigation overflows into water bodies, contribute to water pollution via algae growth (eutrophication) [7,8]. Food security policies must, therefore, be designed to incorporate measures of cultivation of low-input demanding crops with high outputs, such as cassava.

Cassava (*Manihot esculenta*), a woody shrub with a starchy edible root (tuber) is common to most developing regions including Latin America, Asia, and sub-Saharan Africa (SSA) [9,10]. Globally, cassava supports the livelihood of over thousands of farmers, processors, and traders [10]. It has gained prominence as a potential economic empowerment crop partly due to its propagation using inexpensive stem (stalk) residues, which encourages cultivation by farmers of all economic reputes [11]. Furthermore, cassava is touted as a potential food security crop due to traits of efficient use of resources in growth as well as its adaptability to harsh agro-climatic conditions of drought, low soil nutrients, and tropical/subtropical climates [9,10,12]. Several studies have demonstrated the advantages of cassava regarding starch content [25-30 wt.% (wet basis)], water use efficiency, energy potentials, and yields, relative to most starch crops [13–15]. Furthermore, large demands for cassava starch exists, with diverse applications in the pharmaceutical, livestock feed, ethanol, adhesive, and food manufacturing industries [16]. Cassava has, therefore, been projected as a potential food security and economic empowerment crop for South Africa [16,17]. Towards implementation decisions, cultivation trials showed suitability for growth in the various agro-ecological zones of Limpopo, Gauteng, Mpumalanga, and Northern KwaZulu-Natal provinces [17,18].

1.1.1 Challenges to the industrialization of cassava processing in Africa

In Africa, cassava cultivation and processing is largely marginalized to subsistence growers in rural poor areas in the cultivation regions, and often aimed at low-value food or income generation [10]. Strategic advancement of cassava could therefore contribute to rural poverty alleviation and increase food security, which could be achieved through expansions in the industrial uses and market avenues. It has been estimated that nearly 62 wt.% (wet basis) of worldwide consumption is in Africa [19], indicating the importance of the crop to the region. However, industrial processing to starch (below 1 wt.% of produce) and starch derivatives (below 1 wt.% of produce) for export is insignificant within the region, with consumption as traditional processed foods contributing as high as 89% of total production [20]. Africa's full economic potential for cassava is constrained by the dominating traditional processing techniques which are characterized by inefficient mass and energy conversions, and capacity constraints [21]. Industrialization of cassava processing is therefore vital to realize the cultivation and economic potential, as well as global competitiveness. However, the composition of the cassava, unreliable feedstock supplies, and process energy demands reportedly pose hurdles to its industrialization [22,23].

1.1.1.1 Composition of cassava

Various reports [22,24,25] suggest that low shelf-life (2-3 days) due to high moisture (65-70 wt.%), incidences of compositional cyanogen, and low-protein content of less than 1 wt.% (wet basis) (Table 1.1) present key challenges to the economic development of cassava. However, the challenges of low-protein and naturally occurring cyanogen are more pertinent to direct consumption as food due to nutritional and food poisoning risks, respectively [26,27]. The low protein concern is irrelevant to industrial transformations to products such as starch, flour, or sweeteners. Additionally, studies have shown that process unit operations such as grating, boiling, drying, and fermenting could eliminate or reduce the cyanogen in the products to acceptable limits [26–29], thus not an imminent concern. Therefore, the rapid postharvest deterioration due to high moisture remains the major constraint to industrialization [21,30]. This is further compounded by the high costs of transportation of the cassava to processing sites, due to the high water contents (65-70 wt.%) [31]. Overcoming these challenges requires dehydration or drying of the produce to storable intermediates such as dried cassava chips, flour, or starch [31,32].

Table 1.1: Composition of cassava roots [33]

Component	Fresh weight (per kg basis)	Dry weight (per kg basis)
Moisture	655 g	157 g
Protein	10 g	14 g
Lipid	2 g	5 g
Starch	324 g	806 g
Fiber	15 g	40 g
Ash	9 g	18 g
Calcium	260 mg	960 mg
Phosphorus	320 mg	810 mg
Iron	9 mg	79 mg
Sodium	20 mg	NA
Potassium	3.94 g	NA
Vitamin B2	0.4 mg	0.6 mg
Vitamin C	340 mg	NA
Niacin	6 mg	8 mg
Cyanide	NA	16 g
Copper	20 mg	NA

NA = not available

1.1.1.2 Unreliable feedstock supply

Sustainable operations of the few industrialized cassava facilities in Africa are reportedly constrained by unreliable feedstock supplies. For instance, a state-owned cassava starch factory in Ghana (Ayensu Starch Factory) has been operating erratically since establishment in 2002 due to challenges of unreliability in energy and feedstock supply [34]. Similar feedstock security challenges have been reported for scaling up of ‘gari’ (a traditional food product from cassava) in Nigeria [21]. The feedstock security challenge has been attributed to perceptions of cassava as a drought crop and food for the poor, resulting in high demands during drought seasons and neglect in the rainy seasons where other crops are abundant [35,36]. Furthermore, farmers reportedly encounter economic losses due to poor pricing or rotting of the cassava when there is excess in the rainy seasons, and therefore shift to the cultivation of more desirable crops [36]. Hence, the successful industrialization of cassava will require intensification and uninterrupted cultivation measures to ensure sustainable feedstock supplies for continuous operations.

1.1.1.3 Energy demands and costs

In general, the processing of cassava roots is an energy-intensive activity due to its high water content and bulky nature [21,37]. Sriroth et al. [38] reported thermal energy and electricity consumption of 1600-2500 MJ and 170-250 kWh (respectively) per ton of cassava starch processed. Pingmuanglek et al. [39] also reported drying energy contributions of ~ 69% of the total production energy (2008 MJ/ton) for cassava starch processes. Thus, modern energy for the mechanized units and drying operation (electricity for process equipment, fuels for thermal energy needs) are vital to industrialization of cassava processing.

Regional prevalence of unreliable modern energy supplies [40–42] is foreseen as a risk to the industrialization in Africa. In addition, escalation or instabilities in prices of such energies in the region impacts profitability of the industrialized processes [23,43]. For instance, while energy contribution to cassava starch processing in Thailand constitutes about 14% of production cost [44], its contribution to production costs in similar processes in Nigeria ranged from 20–25% [12], which signifies the importance of energy to the economic viability of the industry in Africa.

1.1.2 Cassava residues-based bioenergy and biorefinery prospects

Based on the aforementioned challenges, the prospects for intensifying cassava cultivation and industrialization in South Africa must incorporate measures of sustaining production growth to ensure sustainable feedstock supplies, and processing of the crop into high-value and storable products, achievable with advanced mechanized technologies. Scenarios of poor accessibility to affordable and reliable energy resources for the industrialization of the cassava sector calls for alternate solutions to sustainable energy sourcing or supply. Sustainable energy options must be cost-effective, locally available, and environmentally friendly, with renewable bioenergy generation using the cassava biomass residues, such as stalks (field residues) and peels or bagasse (process residues), proposed as promising options [11,39,45].

Furthermore, co-production of valuable bio-products and energy using biomass resources, termed biorefinery, is emerging as a more sustainable approach to utilize biomass resources [46]. In biorefinery processes, bioenergy is often the dominant but low-priced product, which includes thermal heat, bioelectricity, and biofuels (biogas, biodiesel, bioethanol). The bio-products on the other hand are high-value products though usually attained in low quantities and include bio-based fertilizers, chemicals, pharmaceuticals, and nutrients among others [46]. Thus, the bio-products could improve the cost-effectiveness of the biorefinery process whilst the bioenergy provides energy for self-use and additional revenue generation [47].

In recent years, several prospecting efforts resulted in innovative and cost-effective technologies for some high-value bio-products, which increased commercial interests, with platform biochemicals such as organic acids (e.g. succinic acid) leading the prospects [48,49]. Various experimental works have demonstrated the potential of cassava residues-based integrated biorefinery processes for such organic acids [50–52]. The cassava residues biorefineries may therefore ensure efficient use of the waste resources, while contributing to job creation and additional revenue streams for growers and processors, hence, a potential catalyst to sustainability of the African cassava industry.

1.1.3 Constraints to industrial uptake of the cassava waste biorefineries

Industrial uptake of the cassava waste biorefineries (CWBs) is hampered by uncertainties surrounding reliable feedstock supplies [16,45], techno-economic feasibility, and long-term sustainability (economic, environmental, and social) of the biorefineries [50,51]. Sustainability, as a concept, emerged from considerations of sustainable development that has been defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [53,54], and advocates for development having fundamental stability from three dimensions- economic, environmental and social [54,55]. Several global sustainable development policies are gradually leaning towards the 3D sustainability criteria, exemplified by the proposed framework for Sustainable Development Goals (SDGs) in the '2030 Agenda for Sustainable Development' [56].

Concerning the cassava industries, regardless of the prospecting efforts for cassava intensification for food security and economic empowerment in South Africa [17,18], which could enhance investor confidence regarding reliable feedstock supplies for industrial processing, little has been done on its industrialization. Meanwhile, high local demands exist for cassava products. For instance, in the year 2016, cassava starch imports of nearly 15.4 thousand tons, valued at R116 million, were the second-largest starch product import, preceded by 35 thousand tons of dextrin/other modified starches worth R465 million [16]. The technical and economic performances of cassava industries, including the associated wastes biorefinery industries, have not yet been explored, which poses limitations to investment decisions. Demonstrations of the techno-economic feasibility and sustainability of the cassava residues biorefineries are therefore imperative and influential to the uptake and implementation, as it will enhance governmental interests and investor confidence.

1.1.4 Techno-economic viability and sustainability demonstrations for biorefinery processes

Techno-economic assessment (TEA), involving simulations of processes and financial models using established experimental or technical data and advanced simulation software such as Aspen Plus® or SuperPro Designer, is a well-developed tool that has been extensively applied in technology or process feasibility assessments. Likewise, sensitivity assessment to ascertain economic impacts of changes in process or economic variables such as product yields or prices during TEA modelling is established [57]. Implementation of TEA, particularly in prospective projects, could therefore help obviate or mitigate investment failures or risks. TEA modelling has been widely applied in various bioenergy or biorefinery feasibility studies and found adequate for process and economic feasibility demonstrations. For example, Aspen Plus® based comparative TEA for biorefinery systems for sugarcane juice and residues [58–61], wood residues [62], and olive stone residues [63] have been demonstrated. Similar modelling based comparative TEA demonstrations for the prospective cassava wastes biorefineries could help establish the process and economic feasibility, as well as identifying avenues for profitability enhancement, which are essential for investment.

In addition, the sustainability (environmental, economic, and social) of prospective biorefineries has received growing attention in recent years. Several studies on sustainability assessments for bioenergy or biorefinery systems were attentive to the environmental dimension using the well-established environmental Life Cycle Assessments (eLCA) via simulation software such as SimaPro, openLCA, or GaBi, while the economic and social dimensions received little considerations [54,64]. Pertinent to the sustainability assessments is the emerging concept of Life Cycle Sustainability Assessment (LCSA) that proposes appraisal of the environmental, costs, and socio-economic impacts throughout a system's life cycle [65,66]. A proposed methodology for the LCSA suggests evaluation of the environmental aspect as the conventional eLCA, the costs aspect [termed Life Cycle Costing (LCC)] determined as the accrued costs from each stage of the life cycle, and the social aspect [termed Social Life Cycle Assessment (sLCA)] assessed as the socio-economic impacts like job creation among others [67]. Implementation of LCSA for the prospective cassava wastes biorefineries could therefore enable identification of avenues for improvement in associated environmental, costs, and socio-economic impacts, thus, promote sustainability of the biorefineries. Similar to the TEA, the eLCA is well established and could be performed using applicable software suites such as GaBi or SimaPro which are equipped with an extensive database on environmental impacts of related processes [64].

1.2 Research motivations

The agronomy benefits of cassava, including drought tolerance and high starch (used for food) and biomass yields compared to most crops, support potential for viable food and bioenergy developments [12,45,68]. Cassava has, therefore, been proposed as a feasible food and bioenergy security crop for South Africa, which can mitigate the impacts of frequent droughts, diminishing agro-resources (e.g. arable land) and high fossil-energy consumption [16,17,45], and promote socio-economic empowerment (e.g. job creation and livelihood support for farmers and food/bioenergy processors) [35]. Moreover, demonstrated cultivation potentials in different provinces including Limpopo, Gauteng, Mpumalanga and Northern KwaZulu-Natal [17] support feasibility for capacity expansions.

Relative to the established cassava producers in Africa, such as Nigeria and Ghana, the regional cassava sector is said to be globally uncompetitive [12,23]. This has been attributed to setbacks of low crop yields due to poor traditional farming methods [32], and prevalence in low-value traditional food uses amidst well-established high-value industrial applications (e.g. maltodextrin and glucose syrup) [12,23]. The setbacks have been ascribed to the high costs of investment for requisite mechanized technologies [12,21], and the high costs and unreliable supply of process energy and feedstock for sustainable industrial operations (detailed in section 1.1.1) [12,23]. This calls for sustainable industrialization measures [12,18,23], which must be taken into consideration in the cassava industry visions and implementation strategies for South Africa.

In this regard, restructuring of the regional cassava industry into a biorefinery that produces food (crop starch), residues-bioenergy, and high-value bioproducts could sustain the industrialization and global competitiveness. Sustainable mechanization of the cassava processes facilitates industrial developments but is also reliant on inexpensive and reliable modern energy (electricity and fuels) for viable operations. Modular bioenergy systems, based on the crop residues, could be feasible energy solutions for such industrial scenarios [69]. Moreover, with the prospective expansions in the cassava cultivation and processing industries, generation of ample residues (from both cultivation and processing) for the bioenergy can be envisaged, which will ensure sustainable feedstock supply for the biorefineries. The crop residues-bioenergy options, which are renewable alternatives with potential benefits of environmental savings, may provide solutions to the environmental burden limitations of the conventional energy supplies, which is mainly coal-based power and fossil fuels for South Africa [70]. Furthermore, potential for co-production of bioenergy and high-value bio-products (such as organic acids) using the cassava biomass residues (biorefineries) has been established [50,51,71]. Together with the generated bioenergy, the bio-products could provide additional revenues, which may enhance the economic benefits of the biorefineries. The residues-based biorefineries could, therefore, enhance sustainable industrial developments of cassava. Sustainability of the residues-biorefineries is, however, important to their successful adoption and commercialization.

1.3 Research objectives

The main objective of the study was to ascertain the technical feasibility, and the sustainability (environmental, economic, and social) of cassava wastes biorefineries (illustrated in Fig. 1-1), within the socio-economic context of South Africa. To achieve this objective, a series of five (5) studies were considered, which had the following specific objectives:

1. To perform a comparative assessment of primary residues based-bioenergy (biogas/bioethanol) potentials for cassava against those for established starch crops in South Africa [cassava (stalks + peels), maize (stover + cobs), potato (peels), wheat (straws + chaff), millet (stalks), sorghum (straws + shells)], aimed at a framework for

selecting starch crops based on their potential for integrated starch-bioenergy biorefineries via a multi-criteria analysis.

2. To develop Aspen Plus® process and economic models for three scenarios of biorefinery processes focused on resource (energy, water, and biofertilizer) recoveries from the conventional treatment of integrated cassava starch wastes [wastewater (CWW), bagasse (CB), stalks (CS)], which include:
   a. Conversion of integrated CWW and CB for thermal energy (starch drying air) and liquid biofertilizer recovery.
   b. Conversion of CWW and CB plus cassava stalks (CS) for Combined Heat & Power (CHP) and liquid biofertilizer recovery.
   c. Conversion of integrated CWW+CB+CS for CHP, solid biofertilizer, and treated water recovery.
3. To develop process flowsheets and economic simulations for integrated cassava starch wastes (CB+CWW+CS) based biorefinery pathways, which include:
   a. Production of combined heat and power from cassava stalks integrated with biogas from cassava starch wastewater and bagasse.
   b. Integration of cassava starch wastewater and bagasse based ethanol production with stalks-based combined heat and power.
   c. Conversion of cassava starch wastewater, bagasse, and stalks to bioethanol and in-house enzymes, integrated with stalks based combined heat and power production.
   d. Co-production of glucose syrup (GS) and bioethanol from the conversion of cassava starch wastewater, bagasse, and stalks, integrated with stalks-based combined heat and power production.

e. Co-production of succinic acid (SA) and bioethanol from the conversion of cassava starch wastewater, bagasse, and stalks, integrated with stalks-based combined heat and power production.

4. To evaluate the environmental impacts and perform Life Cycle Sustainability Assessments (environmental + economic + social) for the five proposed cassava wastes biorefineries in objective 3 as well as for the conventional wastes treatment, based on the Aspen process models and the environmental life cycle assessment simulations developed in SimaPro.

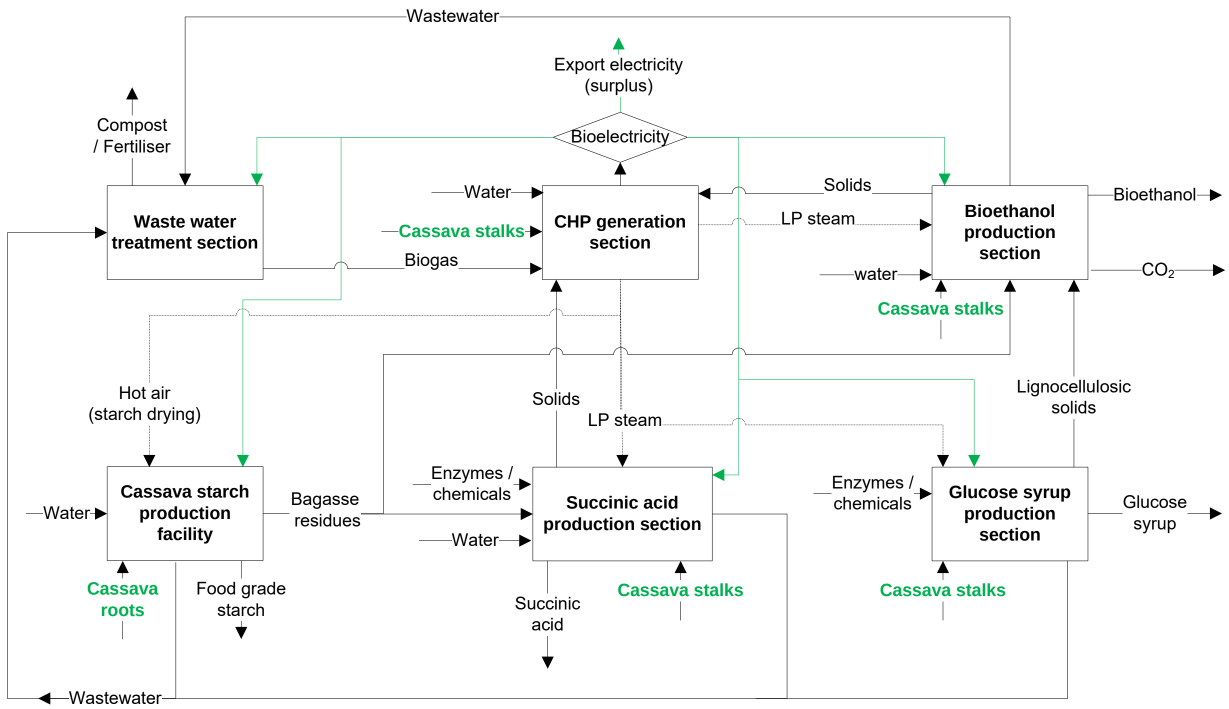

Fig. 1-1: Schematic diagram of the integrated cassava wastes biorefinery

1.4 Research novelty

The present study demonstrates novelty in the conceptual design of the cassava wastes biorefinery (CWB) schemes (see Fig. 1-1, section 1.3), relative to the existing cassava starch facilities' (CSF) energy sourcing from external grid power and fossil fuels [72,73], and the current waste management schemes involving anaerobic digestion (AD) of the CWW & CB to produce biogas for starch drying heat, wherein the digestate and CS are disposed into watercourses and burnt, respectively [72,73]. In particular, the integration of unique circular economy strategies in the CWB designs allows for total waste resource recoveries and advanced biorefinery conversions of the integrated wastes (CWW, CB, CS), with potential beneficial synergistic total in-house energy generation for self-use (both CSF and CWBs) and economic/environmental footprint enhancements. The proposed process schemes utilize waste streams as feedstock for increasing the number of products obtained from the cassava plant instead of relying on tubers only, which can interfere with food security. In addition, the shared wastewater treatment and the combined heat and power (CHP) generation sections by both the CSFs and the proposed CWBs (see Fig. 1-1, section 1.3) ensures the use of larger process equipment with derived benefits of economies of scale. Therefore, the study contributes to knowledge on sustainability enhancement strategies in the cassava industries, including energy self-sufficiency, food security, environmental burden mitigations, and economic beneficiation from integrated cultivation (CS) and process (CWW, CB) wastes-based biorefineries.

1.5 Research contributions to knowledge

In general, the study provides comparative economic & environmental sustainability models for alternate CWB schemes, which contributes to knowledge on strategies for long-term sustainability and profitability enhancements in the cassava industries as follows:

(i) Production of energy and valuable bioproducts (biorefinery) using the cassava starch wastes (CWW, CB, CS), and use of the energy in the CSFs, can contribute to sustainable energy supply for uninterrupted CSF operations while maximizing economic benefits from surplus sales. **Specific objective 1** involved a systematic approach to the comparative holistic benefits assessments (crop starch & residues-bioenergy) for cassava vs. the established starch crops in South Africa, thus, assists with knowledge for decision support in the selection of sustainable feedstock for integrated starch-bioenergy biorefineries.

(ii) Cost-effectiveness of the potential CWB pathways can influence investment decisions. **Specific objectives 2 & 3** provided a framework for selecting and integrating economically viable products in the cassava waste treatments or biorefinery conversions, which helped unravel the techno-economic requirements and insights for commercial feasibility for integrations into the cassava starch processes.

(iii) Even though knowledge of the economic viability of the CWBs serves as an important implementation decision criterion, the environmental burdens of the processes equally provide a strong implementation basis when long-term ecological impacts and related mitigation costs are taken into consideration. Furthermore, the long-term sustainability of the biorefineries calls for an all-inclusive evaluation of the derived social, economic and environmental benefits or detriments [67], which are influential to the adoption decisions by stakeholders such as policy makers (e.g. governments) and investors [74]. **Specific objective 4** unraveled the long-term environmental impacts and sustainability (environmental, economic, social) of the proposed CWBs, thus, support the identification of promising and sustainable value chains for implementation decisions.

(iv) Specific to the context of South Africa, the findings provide salient indicators for feasibility and long-term sustainability of the CWBs for considerations in the prospects for expansions in cassava cultivation, thus, contribute to informed implementation policies and investor confidence for near term applications.

1.6 Thesis layout

The structure of the thesis is summarized in Fig. 1-2. The background, motivation, objectives, research novelty and contributions of the study are given in **Chapter 1**. **Chapter 2** reviews cassava starch and residues-based bioenergy/biorefinery prospects, as well as related studies and methodologies on techno-economics and sustainability assessments. The synthesized methodology followed to achieve the study objectives is presented in **Chapter 3**. **Chapter 4** addresses objective 1, presented as a paper- 'Estimating the bioenergy potential in integrated residue-based biogas or bioethanol and starch production systems for advancing the development of agricultural bio-economies'. **Chapter 5** is a paper that assesses the potentials for integrating resource recoveries into conventional waste treatment (objective 2). **Chapter 6** is a paper on the techno-economic evaluations of the cassava wastes biorefineries (objective 3). The environmental impacts and sustainability of the biorefineries (objective 4) are discussed in **Chapter 7**, which has been presented as a paper. **Chapter 8** provides general discussions, conclusions, and future study recommendations based on the research findings.

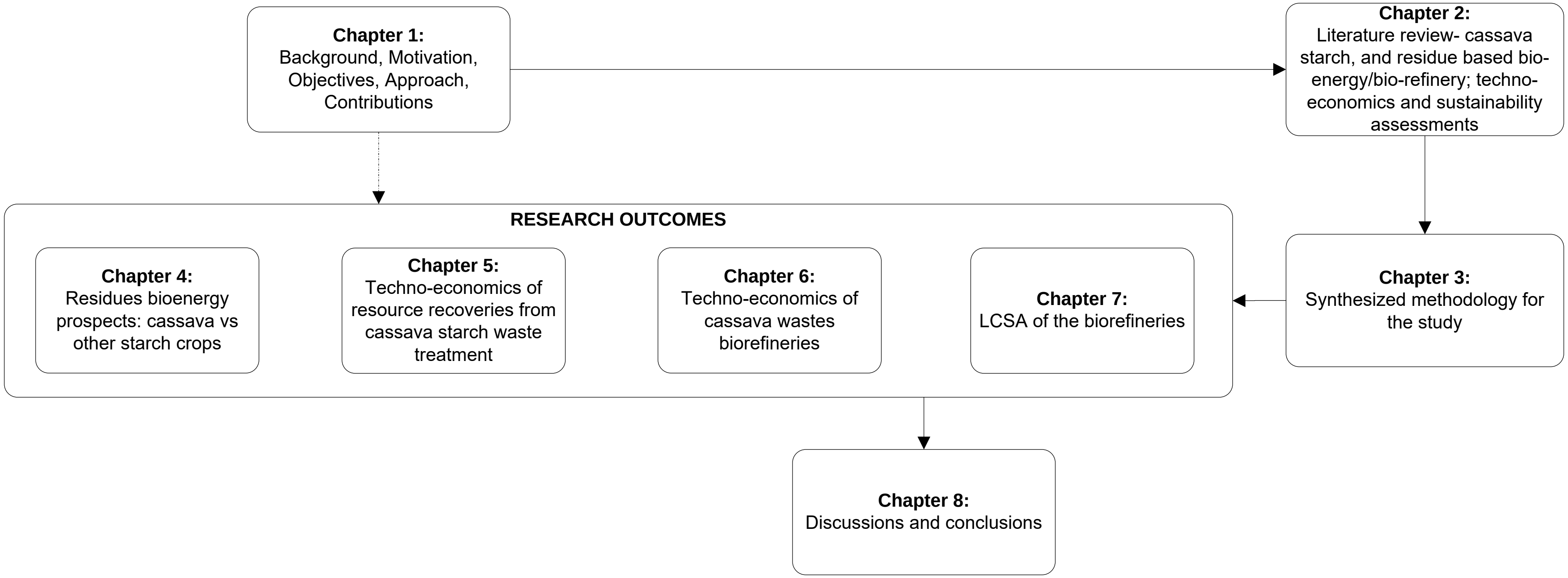

Fig. 1-2: Flow diagram of the thesis layout

2 Literature review

2.1 Introduction

This chapter discusses relevant literature to the study. Pertinent to the food uses of cassava, extracted root starch has been selected due to widespread uses as an intermediate or raw material in diverse food industries. Thus, global starch and associated derivative markets, as well as demands and prospects for South Africa are discussed in sections 2.2. Cassava biomass residue types and generation capacities are highlighted in sections 2.3 and 2.4, while demonstrated biofuel (biogas, bioethanol) and biorefinery developments are detailed in sections 4.2.1 and 2.5 respectively. Section 2.6 discusses studies and approaches to techno-economic and sustainability assessments for bioenergy, biorefinery or industrial projects. It is worth mentioning that aspects of the literature relevant to the specific objectives of the research have been detailed or discussed in the subsequent papers addressing the specific objectives (Chapters 4-7), thus, only briefly discussed in this Chapter for the avoidance of repetitions.

2.2 Starch markets and regional scenarios

2.2.1 Global perspective

Globally, starch and its derivatives are utilized in the pharmaceutical, textiles, cosmetics, food and beverages, paper, and animal feed industries, which signify the existing high demands. Glucose syrup, spray dried starch, maltodextrins, hydrolysates, and cyclodextrins are the leading derivative products, with demands in 2015 valued at approx. 50 million tons, which was expected to increase by 10 million tons by 2020 [75]. From the referred derivatives, glucose syrup is the largest in volume basis (compound annual growth rate- CAGR of 4.2 and 4.0 % for glucose syrup and maltodextrin respectively), whereas the maltodextrin sector shows the highest economic growth potentials- CAGR of 7% [75]. The growing derivative industry is envisaged to continue, owning to driving factors of growth in the pharmaceutical sector and the rising demand for convenience foods and beverages in most developing nations [75]. For instance, a global market survey of starch and its derivatives in 2012 showed achieved sales of approximately $51 billion, which was projected to reach $77.4 billion by 2018, i.e. increasing at a CAGR of 7.1% [76].

2.2.2 The starch industry in South Africa

An extensive field survey on the starch industry of South Africa by Urban-Econs [16] showed the local starch industry to be largely based on maize, and to a minimal extent on potato and rice. The Department of Agriculture, Forestry and Fisheries [17] reported local productions of 20 thousand tons of cassava starch per annum, which was based on full capacity (60 tons starch/day) projections for a cassava starch facility in Dendron (Northern Province) as at 1999 [77]. However, its present operation or success was unsubstantiated in the recent survey reports by Urban-Econs [16]. Okudoh et al. [45] hinted on failure of the earlier cassava starch projects as a result of feedstock insecurities, attributed to crop infestations by leaf mosaic virus and bacterial wilt diseases. However, disease resistant varieties through genetic breeding have been achieved in recent years [32].

The local starch productions are reportedly insufficient to meet domestic starch and derivative demands, with the high deficits imported from Asia, Europe, the Americas and Oceania at high economic costs to the nation [16]. For instance, data on import volumes and costs indicate the total starch and starch derivatives imported for the year 2016 amounted to ~R674 million [16]. The domestic demands have been growing over the years, with corresponding increments in import quantities and associated costs, as shown in Fig. 2-1a. Irrespective of these high imports, considerable exports also prevail (Fig. 2-1a). From import and export data (Fig. 2-1a), dextrin/derivatives and maize starch are the major imported and exported products respectively, which could be attributed to the dominant maize starch and nominal derivative processors in the local industry [16]. Cassava starch is second to dextrin/derivatives in the imported products portfolio (Fig. 2-1a), signifying the high demands in local industries. For the export sector, the major destinations are mainly African nations, with Lesotho, Zimbabwe, Mozambique, and Angola as leading destinations (~ 75 % of total export value) (Fig. 2-1b). Out of the referred destinations, only Mozambique showed a positive and high annual growth in the starch/derivative imports from 2012 to 2016 (20%), while all the others recorded negative values for the same period (-2 to -9%) (Fig. 2-1b). Sustenance of the export markets, therefore, requires expansions and diversification in products to other destinations with high and growing demands such as the United States (8.94% of total global imports, and annual import growth of 5%) and Philippines (1.26% of global imports, at 5% annual growth) (see Fig. 2-1b).

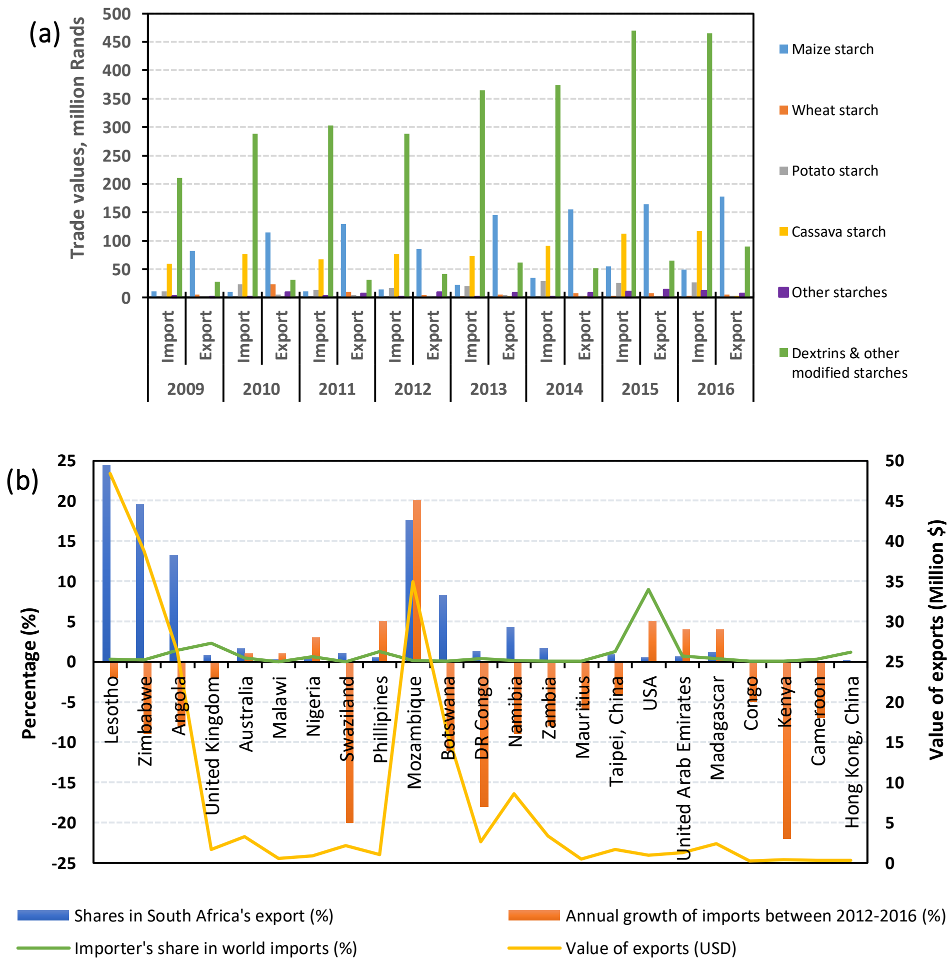

Fig. 2-1: (a) Import vs Export values of starch and its derivatives for South Africa (Source data: As presented in [16]); (b) Year 2016's export potentials and destinations for products of milling industries (malt, starches, inulin, wheat gluten) in South Africa (Source data: [78])

2.3 Cassava bioenergy prospects

Okudoh et al. [45] highlighted the potential of cassava as a biofuel crop in South Africa and Africa as a whole, which was premised on high carbohydrate contents (e.g. starch contents of about 25-30% w/w). The authors discussed the merits and demerits of various pretreatment techniques and technologies to facilitate cassava roots-based biogas production, including chemical, wet-explosion, thermal and ultrasonic approaches. Biofuel processes can be classified into first generation (1-G) and second generation (2-G) depending on the feedstock used. The 1-G involves the conversion of crops such as edible grains or roots (e.g. maize and cassava) via anaerobic digestion (AD) to biogas, or via fermentation to ethanol. The 2-G uses non-food crops or biomass residues as the feedstock, e.g. switch grass or maize stover. Long-term sustainability of the 1-G processes has been debated due to the potential of the feedstock to compete with food uses or cultivation land [79]. The 2-G biofuels based on crop residues is foreseeable as a sustainable path to the collective production of food and bioenergy [80,81] and, therefore, deemed appropriate for South Africa, due to the constraints to the food security, such as declining arable lands and drought [6]. Hence, towards a long-term sustainability strategy, in the present research, cassava bioenergy or biorefinery prospects have been limited to only the associated biomass residues (detailed in section 2.4), while the extracted starch from the crop (root tuber) is designated for food uses.

2.4 Types of cassava biomass residues

2.4.1 Primary residues

After harvesting the cassava roots, the cassava stalks (woody stems) are often left in the field as residues or waste [11]. Average production of stalks has been estimated at 51% the mass of the cassava roots [82], thus an enormous amount generated. The cassava stalks (CS) are vital as seed materials for planting, which constitutes a minimal of 10-20% of the total generated [32]. Reports of minor usage as firewood in some African countries have been cited [11]. Zhu et al. [82] experimentally determined starch contents of the CS to be 22-39 wt.% (wet basis) of the dry matter. The high starch content and high rate of generation of the CS led to an interest in biorefinery applications in recent years [11,82].

Most cassava processes commence with the peeling of the roots, which results in peels generated as biomass residues. The peels comprise about 10-20 wt.% (wet basis) of the roots [83,84], and largely consist of cellulose (37.9 wt.%), hemicellulose (37.0 wt.%) and lignin (7.5 wt.%) [85]. The peels are largely utilized as livestock feed, with high prevalence in certain areas in Nigeria where estimates of up to 68 wt.% (wet basis) of the total generated have been reported [86]. Serpagli et al. [83] also indicated the prevalence of practices of burning, landfilling, or open discard of large portions of the peels, consequently contributing to air and land pollutions.

2.4.2 Cassava starch process residues

Industrial cassava starch extraction involves cleaning of the roots, rasping, fiber (pulp + peels) separation, starch separation, starch dewatering, and starch drying/packaging, as depicted in Fig. 2-2. The extraction process demands large amounts of water, approximately 18 m^3 per ton starch, at percentage uses of 30%- root cleaning, 7%- rasping, 41%- fiber extraction, and 22%- starch separation [44]. This results in large volumes of wastewater generation that typically range between 12-20 m^3/ton starch produced [44,87]. Starch losses of ~0.22 kg per m^3 wastewater (from the fiber separation + starch separation + starch dewatering) have been estimated [44]. Typical organic loadings of the wastewater, at pH of 4.5-5.0, ranged between 11.0-13.5 g COD/l, thus, too high for direct disposal into water courses without treatment [88]. The separated fiber (rasped pulp & peels) in the starch process constitutes the solid residues, called bagasse or pulp. It is mostly obtained as a high moisture (85% w/w) waste, which poses barriers to sustainable storage, handling, or disposal [89]. It is reported that the starch content of bagasse could reach 50% w/w (dry basis) [90]. According to Pandey et al. [33], approximately 1 ton of bagasse (85% moisture) is generated per ton of cassava processed.

Chavalparit and Ongwandee [44] also estimated bagasse generation rate at 1.4 ton (at 35-40% moisture) per ton starch produced.

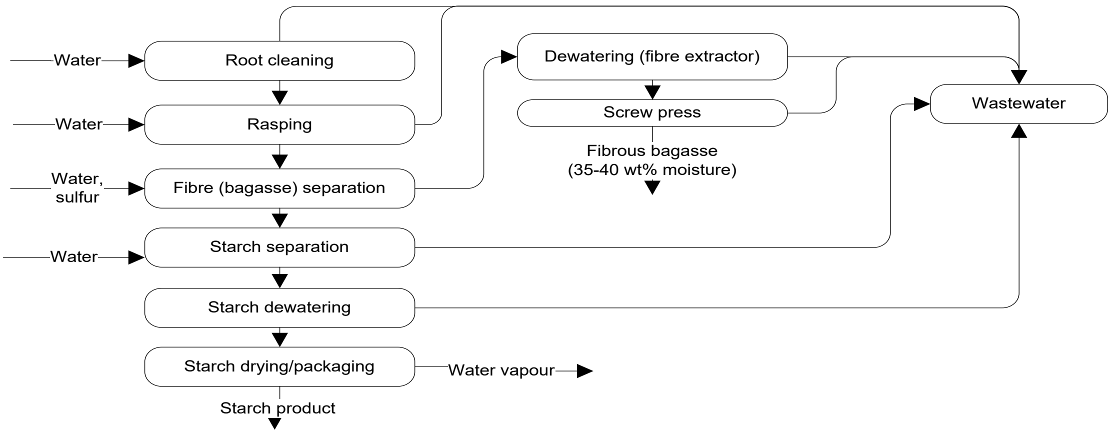

Fig. 2-2: Block flow diagram of a cassava starch extraction process (Adapted from [44])

2.5 Biorefinery developments and prospects for the cassava starch industries

Biorefining has been defined as the sustainable processing of biomass to a range of desirable commodities, which includes livestock feed, food, chemicals, and energy carriers such as liquid fuels and electricity [46]. Typically, the biorefinery involves co-production of bioenergy and bioproducts [46,91]. The bioenergy is usually the major but low-cost products in the biorefinery processes, and includes power generation, biofuels like bioethanol and biomethane among others. On the other hand, the bioproducts are usually high-value products, although usually attained in low quantities, which includes intermediate products used in the cosmetic, food, chemical, and pharmaceutical industries [46]. Hence, the bioproducts are imperative to the profitability of the process, whilst the bioenergy provides energy for in-house uses, as well as additional revenue generation from export sales of surplus [47]. The achievable bioproducts depend on the feedstock characteristics and the processing routes, as depicted in Fig. 2-3.

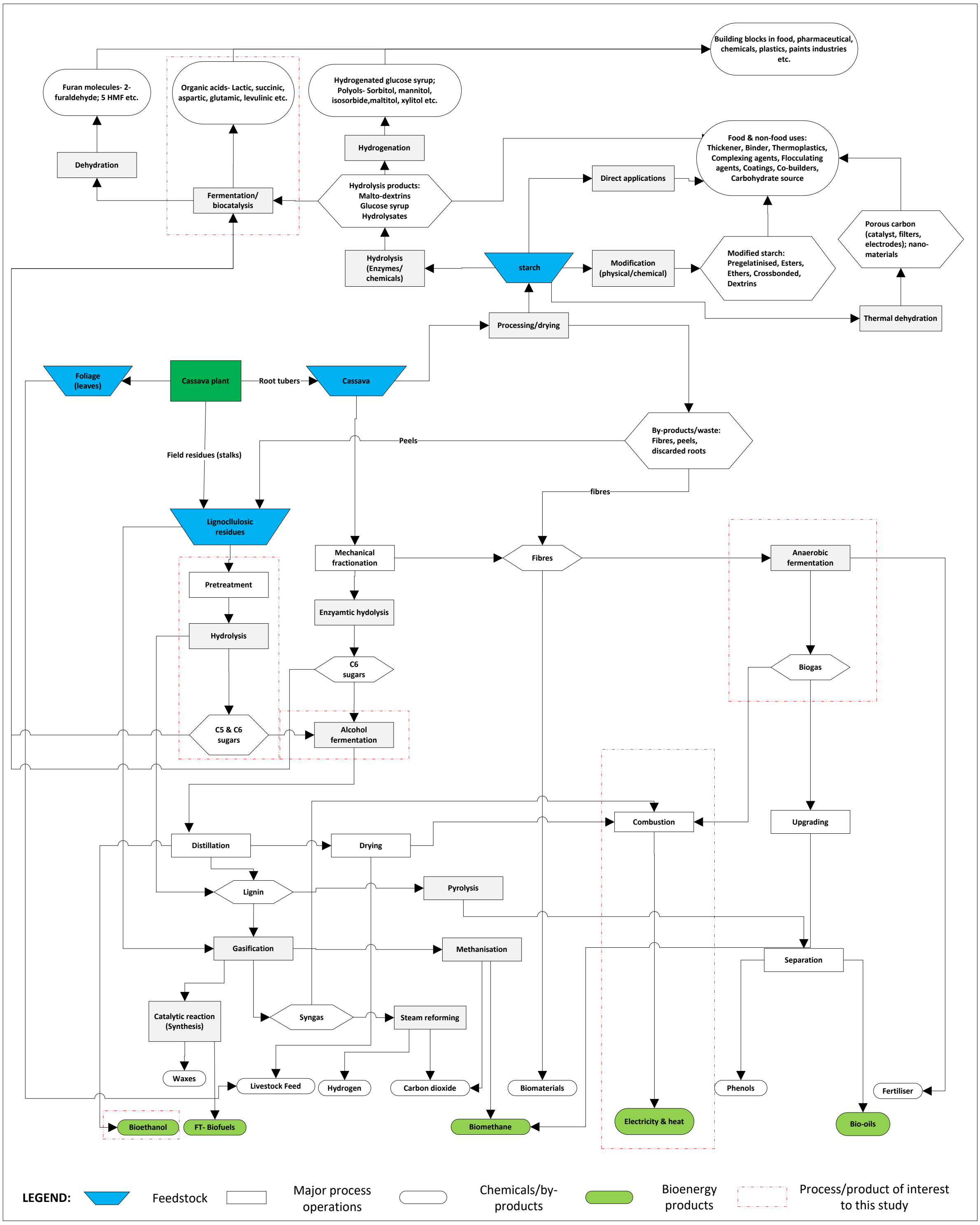

Fig. 2-3: Schematic diagram of probable cassava based biorefinery process routes and products (Author's own synthesis based on [50,51,92–94]).

In recent years, cost-effective technology demonstrations for production of some of the high-value bio-products heightened commercial prospects, with platform biochemicals leading the prospects [48,49]. Werpy et al. [48] assessed the commercialization potentials for platform biochemicals and recommended the following as the top 12 candidates: (i) Succinic, Fumaric, Malic acids; (ii) 2, 5-Furan dicarboxylic acid (FDCA); (iii) 3-Hydroxy propionic acid (3-HPA); (iv) Aspartic acid; (v) Glucaric acid; (vi) Glutamic acid; (vii) Itaconic acid; (viii) Levulinic acid; (ix) 3-Hydroxybutyrolactone; (x) Glycerol; (xi) Sorbitol (alcohol sugar of glucose); and (xii) Xylitol/arabinitol.

Pertinent to the cassava residues biorefineries, studies have shown potential for the production of diverse products, such as biochar, syngas, bioethanol, succinic acid, sugars, and biogas using the residues (summarized in Table 2.1), which informed the studied integrated biorefinery schemes in this research (see Fig. 1-1; section 1.3). The bioproducts selection (glucose syrup- GS, succinic acid- SA, bioethanol) in the present study was informed by technology readiness levels and market demands and growth projections (detailed in section 2.5.4). The following subsections have been limited to the bioproducts of interest to this study, which includes the SA and GS productions. Furthermore, the bioethanol and biogas prospects have been presented in Chapter 4 (section 4.2.1), thus, only related technology developments have been discussed in this section.

Table 2.1: Summary of selected studies on biorefinery exploits for cassava residues

Cassava residue/feedstock type	Study objective	Targeted product(s)/service	Type of technology	Authors
Pulp (bagasse)	Explore a novel biphasic, sequential co-culture system for ethanol / hydrogen production from cassava pulp, requiring neither pre-treatment nor enzymes.	Ethanol and hydrogen	Themophillic fermentation; co- or mono culture systems of C. thermocellum and T. aotearoense	[95]
Rhizome	Investigate effect of feed particle size and inlet air flow (1.98–3.06 m^3/h) on gas production performance.	Syngas (CH_4, CO and H_2)	Modular downdraft gasifier; coupled with heat recovery (return hot flue gas exiting gasifier to the drying and pyrolysis zone of the reactor) and Ni/char catalyst reformer.	[96]
Peels	Production of xylooligosaccharides from cassava peels using an indigenous endoxylanase enzyme- Bacillus subtilis (from abdomen of soil termite).	Xylooligosaccharides (sugars from xylan with food / Pharmaceutical applications)	Alkali extraction, conventional fermentation	[97]
Rhizomes	Demonstrating practical ways of modern biochar production	Biochar	Carbonizer based on semi-continuous, externally heated, retort type, pyrolysis gas burning concept.	[98]
Wastewater (from starch process)	Explore possible routes of clean technology for enhancing water conservation, reduction in raw material loss, and energy conservation in the cassava starch industry.	Implementation of cleaner production in starch factories (minimising material loss, water / energy conservation), biogas	Up-flow anaerobic sludge blanket (UASB) digester	[44]
Wastewater (from starch process)	Assess the carbon footprint (CF) of cassava starch production using in-house biogas, compared to the previous use of fuel oil	Biogas	Up-flow anaerobic sludge blanket (UASB), Anaerobic fixed film reactor (AFFR), Covered lagoons	[72]
Bagasse (from starch process)	Developed succinic fermentation process for cassava bagasse hydrolysate using porous polyurethane filler (PPF) as a carrier for C. glutamicum immobilization, and mixed alkalis (NaOH and MgOH) as pH regulator.	Succinic acid- primary product; lactic acid & acetic acid- by-products	Porous polyurethane filler (PPF) as a carrier for C. glutamicum immobilization; Mixed alkalis (NaOH and Mg(OH)) for regulating pH; Batch fermenters	[99]
Stalks	Using cassava as a model crop on sustainable food and fuel products that have the ability to create synergies between food and energy uses through demonstrations of starch extraction from stalk residues.	Starch- extracted from stalks	Water-based starch extraction	[100]
Bagasse (from starch process)	Tested the effect of thermal treatment of cassava bagasse starch on citric acid production	Citric acid	Solid state fermentation (SSF) in horizontal drum and tray-type bioreactors	[101]
Bagasse (from starch process)	To compare the production of citric acid by SSF in flasks using different proportions of gelatinized starch	Citric acid	Solid state fermentation in column, horizontal drum, and tray-type bioreactors	[102]
Pulp (bagasse)	Investigated potential for using cassava cellulose for ethanol production.	Ethanol	Various fermentation schemes	[103]

2.5.1 Succinic acid developments

Succinic acid (SA) is a platform biochemical with wide-ranging uses, including hydrogenation or reduction to produce the well-known butanediol, tetrahydrofuran, and gamma butyrolactone family of chemicals [48]. SA and its derivatives are used extensively in the plastic, polymer, pharmaceutical, surfactants, and detergent industries, thus, an important product with widespread industrial demands and uses [48,104]. It is largely manufactured using maleic anhydride which is produced from fossil-based butane from petrochemical industries, and minimally through biochemical fermentation of biomass substrates [48,104]. In the biochemical fermentation, specific microbes such as *A. succiniciproducens* or *Eschericia coli* is used to ferment glucose from starch or lignocellulosic biomass substrates [105]. The technical limitations of high production costs for the bio-based fermentation approach hampers competitiveness vs. the petrochemical route [48,49]. To overcome the high cost drawbacks of the fermentation route, co-production with other high-value products has been proposed. Lynd et al. [104] demonstrated profitability for a bio-SA process when integrated with the production of bioethanol. The co-production scheme has, therefore, been projected as a viable means to competitiveness and replacement of the petrochemical based succinic acid [106].

2.5.2 Glucose syrup production

According to Featherstone [107], GS standards require a minimum of 70 wt.% total solids and reducing sugar contents, expressed as d-glucose (dextrose or DE). GS can be produced by acid or acid-enzyme processes, with reported drawbacks of the former involving haze formation, as well as uncertainties towards specific product quality due to high randomness in the process path [93]. The acid-enzyme approach is therefore the most widely used in industrial GS production and is described by Hobbs [93] as follows.

The process begins with pumping the feed starch slurry (~35-45 wt.% solids) into a pressure vessel for acidification with dilute hydrochloric acid (to attain pH of 2.0) at a temperature and pressure of 140-160°C and 5.4 atm (respectively), for ~5-20 minutes. The obtained slurry serves as the starting DE for further conversion in the enzymatic process, termed enzymatic hydrolysis, which is achieved by adding product-specific enzyme(s) in a holding tank until the desired DE is attained. In the scenario of using several enzymes, α-amylases hydrolyze amylose and amylopectin (in starch) to dextrose and maltose; β-amylase breaks non-reducing ends of starch to β-form maltose; glucoamylase then hydrolyzes the produced maltose to the desired glucose (dextrin). Protein and fats are then filtered out of the obtained slurry, a process termed refining, using centrifuges and rotary drum filters, after pH adjustment to 4.5. The next stage, termed clarification or bleaching, involves decolorization and removal of odors/off-flavors (due to components such as hydroxymethylfurfural- HMF) and is achieved by passing the filtrate through a packed bed of granular activated carbon at 69-77°C for about 90-120 minutes, resulting in ~30% solids filtrate. The filtrate is then evaporated using multiple-effect falling film evaporators until the desired solids and reducing sugar contents (≥70 wt.%) is obtained. The cassava bagasse and stalk residues, due to their high starch compositions (section 2.4), have been experimentally assessed as feedstock for GS productions and found promising [108,109].

2.5.3 Considered biorefinery route and technology developments

Lignocellulosic biomass primarily consists of cellulose, hemicellulose, and lignin, as depicted in Fig. 2-4. These components are interconnected and tightly bound together by hydrogen and covalent bonds, which results in the resistance of the biomass to degradation or biological attack [110]. The established lignocellulosic biorefinery pathways, such as the thermochemical or biochemical pathways, incorporate technologies to overcome this drawback. The thermochemical route usually involves thermal aided deconstruction of the biomass into light gases (syngas), including CH_4, CO, H_2, CO_2, and water vapor, termed synthetic gas (or syngas), which is further processed into chemicals or fuels [111]. In the present study, the biochemical technology, focused on sugar-bioconversion platforms, has been selected due to the proven suitability for the co-production of the targeted bio-products (biogas, bioethanol, succinic acid, glucose syrup). Typically, for the referred products, the biochemical conversion process comprises of the following operations: pretreatment, hydrolysis, detoxification, fermentation, product separation & purification (see Fig. 2-3).

2.5.3.1 Biomass pretreatment

In the lignocellulosic sugar bioconversion pathway, the hemicellulose and cellulose polymers are broken down into their monomeric or reducing sugars for subsequent conversion to the bio-products [112]. The techniques used to alter the biomass bonds to expose the referred polymers for conversions to the intermediate sugars (oligosaccharides) are termed pretreatment, which includes physical methods (comminution, extrusion, steam-explosion, liquid hot-water, and irradiation), chemical methods (alkaline, acid, catalyzed steam-explosion), and biological methods (e.g. white-rot fungi) [113]. As illustrated in Fig. 2-4, the first step in pretreatment is the delignification of the biomass to release the cellulose and hemicellulose for subsequent depolymerization into sugars [113]. Furthermore, the internal bonding network of the cellulose is stronger than the hemicellulose's, which results in the latter being more amenable to mild pretreatment conditions such as mild alkaline/acidic conditions, and enzymes, while the cellulose requires vigorous conditions [110]. Several assessments indicate that the pretreatment step is one of the costly stages in the biochemical conversion process for lignocelluloses [110,113,114]. Specific drawbacks of the various pretreatment methods, such as technical constraints due to insufficient separation of the biomass components, inhibitory effects of by-products formed, high energy, chemical, or enzyme demands and costs, and high capital cost of the pretreatment equipment, have been extensively reviewed in literature [49,110,113,114].

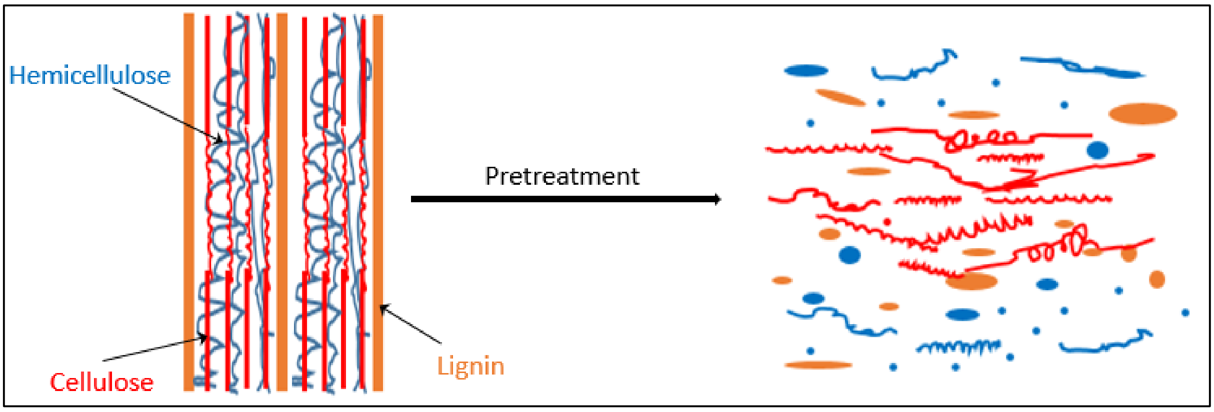

Fig. 2-4: Illustration of the effect of pretreatment on lignocellulosic biomass (Redrawn from [112]).

2.5.3.2 Hydrolysis

The hydrolysis step involves the breaking down of the cellulose and hemicellulose oligosaccharides from the pretreatment step into fermentable monosaccharides using biological agents such as enzymes (e.g. cellulase and hemicellulase), or chemical agents such as acids (e.g. dilute or concentrated HCl or H_2SO_4) [115,116]. Relevant to the enzymatic hydrolysis, blending of the cellulase and hemicellulase, which are engineered to handle the cellulose and hemicellulose respectively, have shown benefits of enhanced hydrolysis yields, operation time, and cost effectiveness [117]. Selected hydrolysis performances for starch biomass residues, including cassava, are presented in section 4.3.1 (Table 4.2).

2.5.3.3 Detoxification

The pretreatment and hydrolysis operations could lead to the introduction or formation of substances that are toxic to the microorganisms in the subsequent fermentation, called inhibitors. Inhibitors could be classified into: (i) Furan compounds from sugars (furfurals and 5-HMF), (ii) Heavy metal ions mainly from the reactor vessels (e.g. nickel, copper, iron, and chromium), (iii) Weak acids (e.g. acetic, formic & levullinic acids), (iv) Raw material extractives (e.g. acidic resins), (v) Phenolic compounds from lignin (e.g. ketones & aldehyde) [118,119]. Hence, the types of inhibitors depend on the composition of the lignocellulosic biomass and the pretreatment/hydrolysis method used [120]. Removal of the inhibitors to enhance the fermentation efficiency is termed detoxification, which includes various techniques that can be grouped into chemical (e.g. over-liming, neutralization using calcium hydroxide, ion-exchange resins, adsorption using activated charcoal, and organic solvent extraction), biological (e.g. microbial, enzymatic), and physical (e.g. membrane-aided, evaporation) methods [118,119]. Remarks for the various detoxification strategies are summarized in Table 2.2.

Table 2.2: Summarized features of the various detoxification methods

Detoxification method		**Remarks**	**Reference(s)**
Biological	Microbes, Enzymes	Milder operating conditions, eliminates further chemical use, minimal side reactions, lower energy demands, environmentally benign, longer reaction time, sugar losses, high costs of enzymes	[118,121]
Chemical	Adsorption with activated carbon	Handles furans and phenolic inhibitors, minimal sugar losses, highly cost-effective	[93,122,123]
	Ion Exchange Resin	Reduce phenolics, some weak acids (acetic acid), resin used can be recycled, scale-up constraints	[124–126]
	Overlimming & neutralization	Addition of $Ca(OH)_2$; high sugar losses	[127,128]
	Organic solvents extraction (liquid-liquid extraction)	Uses organic solvents such as ethyl acetate, trialkylamine; handles furans, phenolics, acetic acid; high cost of operation, longer reaction time	[129,130]
Physical	Membrane separation (ultrafiltration)	Expensive operation, selective removal of inhibitors	[131,132]
	Evaporation (Vacuum evaporation)	Handles volatile inhibitors such as acetic acid, furfural etc.	[57]

2.5.3.4 Succinate fermentation

The essential step in the bio-succinic acid process is the fermentation operation, which involves the bioconversion of the sugars or carbon substrates (e.g. glucose, arabinose, xylose, galactose, mannose, cellobiose) to succinate by certain anaerobic or facultative microorganisms such as rumen bacteria (e.g. *Anaerobiospirillum succiniciproducens*, *Mannheimia succiniciproducens, Actinobacillus succinogenes)* [105,106,133]. However, due to drawbacks of high and expensive nutrients demands (e.g. yeast extracts, peptone, and vitamins) and complexity of the process for the referred bacteria conversions, alternate microbes have been explored, with *Escherichia coli* being one of the promising options regarding advantages of well-known genetic account, modest nutrients requirements and shorter growth times [134]. Apart from the carbon substrate and microbial nutrients, additional conditions essential to the succinate fermentation include a CO_2 atmosphere (supplied through external CO_2 gas sourcing, and carbonates in the nutrients broth such as $CaCO_3$, $NaCO_3$, or $MgCO_3$), a temperature of 37-43 °C, and pH of 6-7.5 [105,134,135]. The pH, CO_2 levels, and sugar or substrate concentration is said to be critical factors to the cell growth and succinate yields [135,136]. For instance, theoretical yields of 1 mol succinate per 1 mol of glucose & 2 mol of CO_2 has been projected for *A. succinogenes* [106].

With respect to cassava as a carbon substrate, several studies have demonstrated suitability for strains of *E. coli* for succinate fermentation using the cassava root starch or bagasse waste. Chen et al. [134] achieved succinic acid yield of 0.86 g/g cassava starch for an *E. coli NZN111* based simultaneous saccharification and fermentation (SSF) process at 40 °C. Similarly, a notable succinate yield of 1.03 g/g cassava starch (92% of the theoretical yield) was shown for a fed-batch SSF based on strain *E. coli KJ122* [135]. Sawisit et al. [137] investigated optimized processes for succinate production using the cassava bagasse (pulp) and an engineered *E. coli KJ122* strain. It was shown that, for a separate hydrolysis and fermentation (SHF) process under anaerobic conditions, succinate yield of 0.82g/g dry bagasse can be attained. On the other hand, a lower succinate yield of 0.70 g/g dry bagasse was shown for an optimized SSF process [12% (w/v) cassava pulp, enzyme loading of 2% AMG + 3% Cel (v/w), pH 6.5 and 39 °C] [137].

2.5.3.5 Product separation and purification

In the succinic acid process, the downstream product recovery and purification involves the separation of the succinate from the fermentation broth, conversions of the succinate salts (favored by the fermenter's pH of 6.0-7.0 as compared to the acid form) into the free acid form, and further purification to remove impurities such as broth nutrients, cells etc. [138]. The recovery and purification stage reportedly accounts for almost 60-70 % of the product costs [139,140]. A major difficulty to the efficient recovery arises from the formation of similar organic acid (e.g. acetic, formic, and lactic acids) and ethanol by-products by several of the succinate producing microorganisms such as the *A. succinogenes*, *A. succiniciproducens*, and *E. coli* [141]. Various studies have led to product recovery enhancement strategies. For instance, direct precipitation of the succinic acid in the fermenter into calcium succinate salts via the addition of calcium hydroxide, followed by conversion into the free succinic acid form through the addition of sulfuric acid, which is recovered/polished via filtration using activated carbon/ion-exchange resins, has been established [138,142]. The associated advantages and demerits, respectively, include higher product recovery (94.2% w/w) and large amounts of solid (gypsum) & slurry (calcium sulfate) wastes generation with consequential treatment costs and environmental concerns [106].

An integrated conventional electro-dialysis and crystallization process, with economic promises for commercial operations, has also been established [106]. In the electro-dialysis operation, ion exchange membranes are used to separate ionic species of the succinate salts from non-ionic molecules or compounds such as polysaccharides and amino-acids, which is driven by a direct electric current [106]. The sodium succinate is subsequently converted to succinic acid as previously described, which is further purified via an evaporative crystallizer that generates the succinic acid crystal products [138]. A reported disadvantage of this process is the substantial succinic acid losses (only 79.6% w/w recovery) and high product contaminants (e.g. 19.9% w/w acetic acid retained in product) [138].

Feasibility of succinate recoveries and purifications using reactive extraction with amine agents (e.g. tri-n-octylamine), due to the ability of the amine agent to selectively extract carboxylic acids whose dissociation are dependent on pH, has been proven [143,144]. A promising process, involving integrated reactive extraction [removed organic acids (e.g. succinic, acetic, formic, lactic acid) and salts), vacuum distillation (handles residual organic acids), and crystallization (4°C, pH 1.0–3.0), which yielded 73% w/w succinic acid recovery with 99.8% (w/w) purity, has been developed [143].

However, for some succinate derivative products, by-passing the succinate conversions to the succinic acid forms in the recovery process could be promising for reductions of the high recovery costs. For instance, a pressurized reactive distillation process, developed by Bioamber, could separate diethyl succinate product for direct conversion into final products such as 1,4-butanediol (BDO)/tetrahydrofuran (THF)/gamma-butyrolactone (GBL) and diethyl maleate via catalytic hydrogenation and catalytic oxy-dehydrogenation, respectively [141,145].

2.5.4 Market trends and prospects for the targeted bioproducts

It is estimated that the bio-based SA is the fastest growing primary bio-product market [49]. For instance, in the year 2013, production of the bio-based SA was estimated at 38 thousand tons, valued at US$108 million vs. the fossil-based capacity of 40 thousand tons (valued at US$100 million) [49]. Recent reports reveal further growth projections in the SA market from US$ 131.7 million (2018) to US$182.8 million by 2023, attributed to the increasing industrial demands for related food, beverage, and personal care products [146]. Similarly, glucose syrup (GS) is the largest derivative market for the starch industry, with a compound annual growth rate (CAGR) of 4.2% [147]. The rising demand has been attributed to the growth in the pharmaceutical and convenience food sectors where GS serves as a major raw material [75]. For instance, the year 2020 global starch and derivatives market valued at

~US$51 billion is projected to increase to US$ 61.5 billion by 2025 (CAGR of 3.9%) [148]. Recent surveys on the existing bio-based products market suggest bioethanol leads with a value of US$ 58 billion [49]. Regarding the technology readiness level (TRL) for the bioethanol and the bio-SA, consensus among various experts suggests the bio-SA is transitioning from demonstration to commercial status while the bioethanol is already at the commercial level [49]. Hence, the selected bioproducts have high market demands with promising commercial prospects.

2.6 Sustainability concerns for biorefineries

The 'sustainability' concept emerged from the 'sustainable development' concept defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [53,54]. Sustainability of a project or service advocates for fundamental stability in its benefits from three dimensions- economic, environmental, and social [55]. Thus, the belief of bioenergy or biorefinery being fundamentally sustainable, based on only the renewability of the feedstock and environmental savings (CO_2 sequestration), has been debated, as the definition of sustainability goes beyond renewability or ecological gains [149].

Integration of sustainability principles in biorefinery designs, with proposed attentions to factors such as food security, environmental and socio-economic impacts, has been encouraged [69,150,151]. Although the sustainability concerns are broad and not totally covered in the scope of the present research, they have been recognized in the conceptual framework design of the study. For instance, only technical capacities of the cassava stalk residues (total generated minus portions required for other uses such as re-planting material) have been considered in specifying the biorefinery process capacities (sections 5.2.1 & 6.2.1.2), thus, eliminates competition with existing social uses. Likewise, only the inevitable stalks and bagasse residues are considered in the biorefinery conversions while the cassava root starch is designated for food uses, thus, eliminating food security concerns. This brings the economic, environmental, and other socio-economic (e.g. job creations, energy security) dimensions to the fore front of the sustainability concerns for the biorefineries under study.

2.6.1 Sustainability assessments of bioenergy or biorefinery processes

2.6.1.1 Economic dimension

Most biorefinery design projects examine economic performance through rigorous economic modelling vis-à-vis technology performances, termed techno-economic assessments (TEA). The economic performances are assessed relative to economic indicators such as gross profit, pay-back period, production cost, minimum selling prices (MSP), and net present value (NPV). However, the cost indicators (e.g. production costs) do not reflect the project's profitability, thus, profitability indicators such as NPV, MSP, and pay-back period are more favored in TEA [54]. The approach usually involves process design or simulations based on experimental or technical data, followed by economic assessments based on the developed processes. For instance, Moncada et al. [62] assessed the economic viability of a wood residues-based ethanol + furfural biorefinery process integrated with different scenarios of energy supplies, using process and economic modelling in Aspen Plus software, and NPV and pay-back period indicators.

2.6.1.2 Environment dimension

Uncertainties and concerns about the environmental benefits of bioenergy or bio-products vs. fossil-based alternatives have been discussed [152,153]. Studies to unravel these uncertainties and concerns are informed by regional context and methods, which limits generalization to other regions [54,154]. Environmental Life Cycle Assessments (eLCA) is a well-established technique for evaluating the environmental consequences (risks, impacts, performance) associated with a product, production process, or service systems [155]. The ISO standard 14040 on eLCA [155] stipulates the basic steps as: (i) Definition of the goal and scope of the study, (ii) Taking inventory on inputs and outputs for the process or product of interest, (iii) Evaluation of related environmental impacts associated with the identified inputs/outputs [Life Cycle Impacts Assessments (LCIA)], (iv) The interpretation of findings in steps 2 and 3 in relation to the study objectives. For eLCA of a production processes, system boundaries usually include the stages of the raw material or feedstock sourcing, the production process, the usage of products, and waste handling [67]. The system boundary could also be defined or narrowed based on the study objective and scope of interest [67]. The outcomes of the eLCA could, therefore, facilitate product development or improvement, public policy formulations, and strategic planning or selection of a choice from alternative options [155].

The eLCA has been widely used for environmental evaluations of bioenergy or biorefinery projects, with a focused interest on comparative assessments of alternate conversion processes for a product, or alternate products from a common biomass feedstock, or bio-products vs. similar fossil-based alternatives [156–159]. Similar eLCA approaches have been applied to cassava-based 1-G bioethanol (using root starch as feedstock) and food processes in some of the leading producer nations, as shown in Table 2.3. The literature on eLCA of cassava applications largely focused on energy-footprint, water-footprints, land-use, or greenhouse gas (GHG) emissions for 1-G bioethanol, commercial starch, or flour processes (as shown in Table 2.3). Conclusively, the present study's findings on the eLCA will fill an essential knowledge gap on the environmental implications of implementing the cassava 2-G (using residues) biorefineries [50,51].

Table 2.3: Summary of some works on environmental assessments of cassava-based industries

Process	Targeted products	Study setting	Description of study	Author(s)
Food	Cassava flour	Southwest Nigeria	Analyzed environmental impacts of cassava flour production processes	[160]
Food	Cassava starch	Thailand, Vietnam, Columbia	Evaluated energy/water consumptions and greenhouse gas (GHG) emissions for cassava starch production technologies using 3 factories as case studies [2 small-scale facilities having capacities 1–2 t starch/day; 1 large-scale facility with capacity of 100–200 t starch/day]	[73]
1-G Biofuel	Ethanol	Thailand	Assessed GHG and water footprint for three commercial cassava bioethanol facilities. The scope was a "cradle-to-gate" i.e. feedstock cultivation + transportation + ethanol conversion and on-site waste management.	[161]
1-G Biofuel	Fuel ethanol	Thailand	Comparative analysis of cassava root starch-based ethanol potentials as gasohol E10 vs. conventional gasoline.	[162]
1-G Biofuel	Ethanol	Vietnam	Examined benefits of cassava ethanol uses as transport fuel via eLCA, per energy efficiency, land use change and GHG emission indicators.	[152]

2.6.1.3 Social dimension

Gheewala et al. [74] assessed the socio-economic impacts of a sugar mill biorefinery complex in Thailand using the UNDP's Human Development Index (HDI), which integrates indices of Education (gross enrolment and literacy rates), Life Expectancy, and Gross Domestic Product (GDP). In their study, the HDI concept was adapted to evaluate influences of the biorefinery on social welfare of the direct and indirect actors or employees of the biorefinery process, which was achieved through dissemination of questionnaires to related stakeholders. The obtained findings were then compared to those of the populace within the community. Although the above approach to assessing the social impact of the sugar mill biorefinery could be applied to the cassava residues biorefineries under study, the theoretical context of the latter poses a limitation. Nonetheless, an adaption where the social benefits are projected as potential job creations, human health impacts, and contributions to energy security has been considered [47,150].

2.6.1.4 Life cycle sustainability assessment (LCSA)

The United Nations Environment Programme, and the Society of Environmental Toxicology and Chemistry (UNEP/SETAC) life cycle initiative described 'Life Cycle Sustainability Assessment' (LCSA) as the evaluation of the environmental, social and economic impacts of a product/system for implementation decision-making, towards a sustainable environment [67]. The LCSA is a concept aimed at evaluating the sustainability (environmental, economic, social) of processes or products along the entire value chain [65,66]. Kloepffer [65] summarized the LCSA as shown in Eq. 2.1.

$$LCSA = eLCA + LCC + sLCA \qquad (2.1)$$

Where: LCSA is Life Cycle Sustainability Assessment; eLCA is environmental Life Cycle Assessment; LCC is Life Cycle Costing; and sLCA is social Life Cycle Assessment.

Ciroth et al. [67] indicated that although a standard procedure for LCSA is still under development by the UNEP/SETAC Life Cycle Initiative, a recommended guideline by the organization is available. The guideline for the eLCA aspect is the same as previously discussed in section 2.6.1.2. The LCC simply refers to the aggregation of all costs directly associated with a product throughout the life cycle [i.e. from raw material sourcing, raw material supply, processing, product use, and end-of-life of product (e.g. disposal, recycling)], and usually reported per functional unit basis to facilitate comparison (e.g. US$/kg product). The LCC concept could be extended to the environmental and social costs (i.e. environmental LCC and social LCC respectively) associated with the product that are directly covered by actors in the life cycle [67]. Since some aspects of the life cycle occur in later periods, such as end-of-life of product, conversion of the costs of the future life cycle stages to present cost values using applicable discount rates has been recommended [67]. The approach to LCC follows a similar approach to the eLCA, which includes: 1. Definition of the study's objective and functional unit, 2. Inventory costs, 3. Aggregate costs by cost classifications, and 4. Explanation of results.

The aggregation of costs by cost categories leads to potential benefits of identifying avenues for cost reduction, as well as monitoring of costs under different scenarios [65,67].

The social Life Cycle Assessment (sLCA) refers to the evaluation of the social or socio-economic impacts of systems or products, and related detrimental or beneficial effects along the life cycle [67]. The sLCA approach follows the ISO 14040 outline for eLCA, namely: (i) Goal and boundary description, (ii) Inventory, (iii) Impact evaluation, and (iv) Interpretation of results. It has been suggested that the definition of the sLCA inventory could encompass all stakeholders in the various geographical locations of the value chain(s), which may include employees, local or regional populace, society (national or global), consumers, or value chain actors (e.g. processors, raw material suppliers, product traders).

Various methodologies for the integration of the procedure or results of the aspects of the LCSA (eLCA, LCC, sLCA), such as the use of weighting factors or normalization of the data, have been proposed [64,66]. The integration, however, has a disadvantage of introducing uncertainties in the outcomes, thus, proposed as an optional step for context-specific purposes [67].

2.6.2 Long-term environmental and economic sustainability assessments using systems modelling approach

System dynamics (SD) modelling is a tool for analyzing dynamic behaviors or performances of assembly of elements or components that work in a synergistic manner (a system) over selected periods [163]. The SD models, therefore, facilitate the holistic analysis of dynamic behaviors of complex systems [164,165]. SD models allow for the capturing of complex systems in both qualitative and quantitative forms by means of causal loop diagrams (CLD) developed based on causal-effects relations amongst dependent variables or components of the system [166–168]. The CLD are then translated into stock-flow diagrams and associated governing equations or relations that can then be entered into SD software such as Structural Thinking, Experimental Learning Laboratory with Animation (STELLA) Architect, or Vensim PLE for the analysis [164]. Hence, the feasibility and accuracy of SD models highly depend on in-depth knowledge of the system, which includes established interrelationships between the elements of the system and availability of real-world data [166,169]. SD modelling, using the referred software, has been applied in cost-benefit and sustainability assessment of crop production and technology uptake for bioenergy development in various regions in South Africa [151,169,170] and Malawi [171,172].

In relation to the long-term economic and environmental impact assessments for the proposed integrated biorefinery systems (i.e. an assembly of multi-process technologies and stages to co-produce the multi-products), the theoretical context poses limitations regarding the needed information for the assessments. In particular, in-depth information on the individual bioprocess technologies' (for the various products- bioethanol, SA, GS, and CHP) energy requirements, practical operation conditions, and mass/energy conversion efficiencies are imperative for their successful integration into a multi-product biorefinery system [47,54]. In this regard, the Aspen Plus ®software serves a useful systems modelling tool that facilitates successful technology integration and process simulations to identify auspicious process configurations that could support the integrated biorefinery systems [57,173]. This is facilitated by the applicable in-house thermodynamic property database and process technologies in the Aspen Plus software. For instance, the Aspen Plus simulations could help predict the needed split amounts of the available biomass feedstock for the bio-products and CHP generation that could ensure total in-house energy supplies for the integrated biorefinery systems. The generated mass and energy balances from the process simulations then provide the needed information for the long-term economic and environmental impact assessments via economic modelling and SimaPro simulations respectively (detailed in section 3.3).

3 Methodology

3.1 Introduction

This chapter presents the approach to designing the conceptual cassava wastes biorefineries (CWB), and the research approach followed to achieve the study objectives (section 1.3). The detailed descriptions for the methodologies are given in the subsequent research papers (Chapters 4-7), due to their relevance to the specific objectives of the papers, thus, only briefly discussed in this section.

3.2 Conceptualizing the cassava wastes biorefinery schemes

In conceptualizing the CWB schemes, in-depth literature on the operations of cassava starch facility (CSF) and biorefinery exploits for the related wastes were considered, as shown in sections 3.2.1-3.2.2. In addition, compatibility of the proposed CWBs with practices in the regional cassava industries was taken into consideration, facilitated by field visits to- and personal discussions with managements of- Ayensu Starch Company Limited (cassava starch facility), Caltech Industries (cassava ethanol facility) and cassava farms in Ghana, the third leading cassava producer in Africa [5].

3.2.1 Capacity projections

It was conceptualized that the CWB facility will be an annex to a cassava starch facility (CSF) that supplies the CB and CWW feedstock, which will be augmented with sustainable fractions of the CS residues from cultivation fields (see Fig. 3-2). A conservative assumption of the prospective cassava production capacities not exceeding 15% of the available arable land potentials for South Africa was made. As a result, the recent (average for 2006-2016) production capacities of Ghana were deemed possible for South Africa, based on estimates that the average cassava cultivation hectares for Ghana for the period 2006-2016 (900 thousand ha) [5] corresponds to ~7.2% of the available arable land for South Africa (12.5 million ha) [174]. Thus, avg. yield (16.1 t/ha) & average annual production (14.49 million t/a; corresponds to 900 thousand ha) data for Ghana (2006-2016) [5], and CS-to-cassava production ratio ranges of 0.51-0.63 [82,175] were considered in the feedstock capacity projections. Relative to the CSFs, typical capacities of 200 t/d starch production have been cited [71], requiring approx. 842 t/d cassava [44]. Pertinent to the CS feedstock, to ensure sustainable supplies for the CWB operations, it was presumed that only 40-80% of the total CS generated is available for the CWB, based on reports of ~10-20% of the generated CS used as planting materials and combustion fuels [100]. Accordingly, the CWB throughput was projected at 7.29 t/h CB (dry mass) [44], 377.83 t/h CWW [176], and up to 450.89 t/h CS (see Appendix B.1).

3.2.2 Hypothesized cassava wastes biorefinery schemes

In the current management systems of the cassava starch wastes, the CWW combined with CB (50% w/w starch [90]) is treated via anaerobic digestion (AD) to generate biogas used for hot air generation for starch drying, followed by disposal of the digestate into watercourses [73,176]. Conversely, management of the CS wastes simply involves open burning in the fields [82]. Consequently, concerns of water and land pollution, and high carbon footprints associated with the prevalent wastes management schemes are inevitable. The CWW+CB biogas is not enough to meet the high energy requirements of the CSF [71], which comprises 1600-2500 MJ thermal & ~90-260 kWh electrical energy per ton starch produced [177]. Meanwhile, the CS waste, due to its high calorific value (16.3 MJ/kg [175]) and starch content (22-39% dry basis [82]), have been explored for similar beneficial resource recoveries as the CB (see Table 3.1). Likewise, the digestate from the AD of the CWW+CB has shown potential liquid biofertilizer benefits in farming due to its nutrients compositions (e.g. nitrogen, phosphate) [71]. The digestate could further be treated to recover usable water and solid biofertilizer [178,179]. Hence, possibilities exist for total resource recovery from the waste treatment.

Therefore, strategies to maximize the waste resource recoveries for beneficial applications have been considered in the conceptualization of the CWB schemes, towards mitigation of the high water/pollution burdens and the energy/economic constraints to the industrial CSF operations. Furthermore, proven bio-product conversions and technologies, and feasible feedstock capacities were taken into account (see Table 3.1). Consequently, two pathways to the CWBs have been hypothesized in the present study: (i) Integration of the CS wastes into the conventional CSF's wastes (CWW+CB) treatment to enhance expansions in the resource recoveries to include reusable water, liquid/solid biofertilizer, and combined heat and power (CHP) for total in-house energy supply for the wastes treatment and CSF operations (see Fig. 3-1a), (ii) Advanced biorefinery conversions of the wastes (CWW+CB+CS), involving integration of high-value bio-products [bioethanol, glucose syrup (GS), succinic acid (SA)] and CHP (Fig. 3-1b), with potential to enhance the economic exploitations for the wastes resources.

Table 3.1: Cassava waste biorefinery exploits and related technology reports

Cassava waste(s)	**Product**	**Experimental/simulation demonstrations**	**Reference(s)**	**Promising or commercial technologies**	**Reference(s)**
CWW, CB, CS	Biogas / CHP	CWW+CB biogas conversion to CHP using gas-engine	[71,72,175,176]	Steam boiler/turbo-generator; gas-engine/alternator system	[57,71,180]
CB	Succinic acid	Separate hydrolysis and fermentation (SHF); Simultaneous saccharification & fermentation- SSF [12% (w/v) CB loading, 2% AMG + 3% Cel (v/w), pH 6.5 & 39 °C]	[99,137]	Enzymatic hydrolysis (EH); Commercial enzymes (α-amylase; gluco-amylase, cellulase); *E. coli KJ122* fermentation	[48,49,137]
CB, CS	Bioethanol	SHF and SSF [using *S. cerevisiae* (yeast) or *Z. mobilis* (bacteria)]	[181–183]	EH or Dilute H_2SO_4 pre-treatment plus EH; Commercial enzymes or onsite enzyme (multi-enzyme) production; *Z. mobilis* fermentation	[49,57,183]
CS, CB	Glucose syrup	Acid or acid-enzyme or enzyme hydrolysis	[108,183]	Acid or acid-enzyme hydrolysis; purification (centrifuging, activated carbon)	[93,108]

3.2.2.1 Waste resource recovery schemes

Three (3) wastes resource recovery schemes from the CSF waste treatment (Fig. 3-1a) have been considered: (I) CWW+CB conversion to thermal energy + liquid biofertilizer, (II) CWW+CB+CS conversion to CHP + liquid biofertilizer, (III) CWW+CB+CS conversion to CHP + solid biofertilizer + usable water. To facilitate the assessment of energy self-sufficiency for the cassava starch industries, the augmenting CS wastes for the scenarios (II) and (III) was limited to the available CS generated by the host CSF's cassava feedstock farms, estimated at 343.54 t/d (14.32 t/h) (see details in Appendix B.1). In relation to the CHP generation (II-III), due to the combined CWW+CB based biogas and the CS fuel considerations, a dual-fired (biogas, CS) steam-boiler/turbine-generator system have been considered [57,180]. It is anticipated that such waste resource recoveries and re-use in the cassava industry (e.g. biofertilizer applications in cassava cultivation) could serve as a short-term circular economy solution to the energy, cultivation, and cost constraints to the sustainable industrial developments in the starch sector.

3.2.2.2 Advanced biorefinery schemes

For the advanced CWB approach (depicted in Fig. 3-1b), five (5) conceptual scenarios were considered: (I) CB + CWW biogas plus CS to produce CHP, (II) CB+CWW for producing bioethanol, and 100% of CS by-passed to CHP, (III) CS+CB+CWW for bioethanol with 90% CS by-passed for CHP production, (IV) CS+CB+CWW for co-production of GS, bioethanol, and CHP with 90% CS by-passed to CHP production, (V) CS+CB+CWW for co-production of SA, bioethanol, and CHP with 90% CS by-passed for CHP production. It is worth mentioning that the 90% CS by-pass in scenarios (III)-(V) is an Aspen Plus simulation predicted minimum amount that ensures feasibility of total process steam supply for the considered CWB schemes. The advanced biorefinery schemes were aimed at higher economic exploits for the wastes (i.e. conversion into high-value bioproducts with wide-spread industrial uses) while ensuring environmental benefits and total energy supplies for both the CWB and CSF.

In the CWB process concepts, the hydrolysis schemes involved only enzymatic hydrolysis (EH) of the CB [to produce hexose (C6 sugars)] for scenario (II) [183], and dilute acid pre-treatment (H_2SO_4) of the CS+CB [to produce pentose (C5 sugars)] followed by EH of the derived solids [yields C6 sugars] for scenarios (III)-(V) [109]. The referred hydrolysis schemes were based on reports of recalcitrance of the CS to direct EH due to the woody nature [109]. Thus, scenarios (II) and (III) involve C6 bioethanol and C5+C6 bioethanol, respectively. The scenarios (IV) and (V) are similar to the (III), except for the diversion of the C6 sugars for GS and SA productions, respectively. Furthermore, uncertainties surrounding enzyme costing and impacts to the economics of biorefineries have been cited [184]. To ensure reliability of the enzyme's costs impacts in the CWBs, onsite enzyme productions have been considered in the scenarios (III)-(V), which followed similar investigations by the National Renewable Energy Laboratory (NREL) [57].

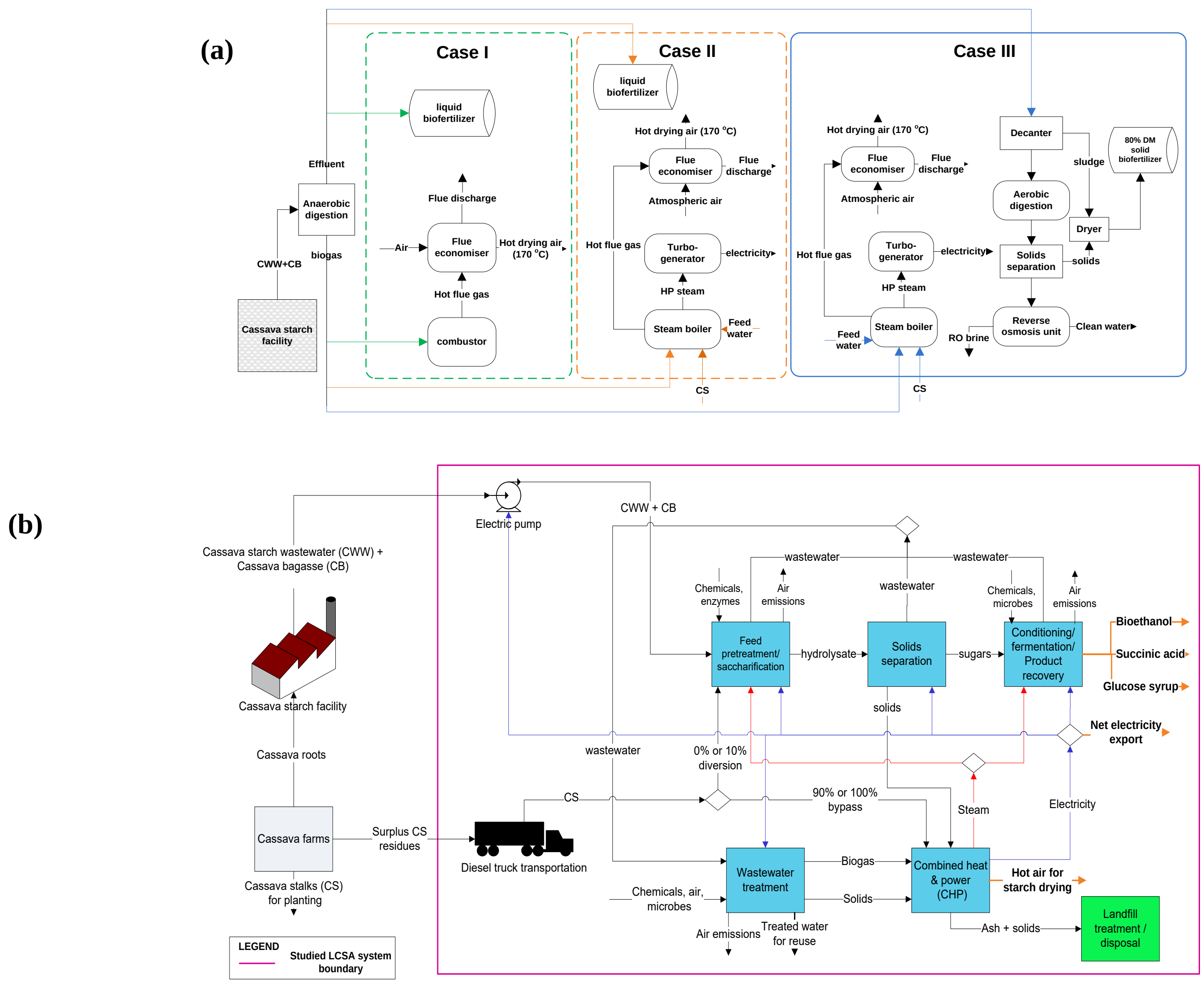

Fig. 3-1: Schematic diagram showing the conceptual schemes for the cassava starch wastes biorefineries- (a) Resource recovery schemes from the cassava starch waste treatments, (b) Advanced biorefinery conversions for the cassava starch wastes.

3.3 Research approach and assessment indicators

The conceptual approach followed to achieve the research objectives [techno-economic modelling (TEA), environmental life cycle assessment (eLCA), life cycle sustainability assessment (LCSA) (section 1.3)] involved computer aided simulations using applicable software, as summarized in Fig. 3-2. The following sub-sections (3.3.1-3.3.2) present the research approach and assessment indicators considered for the referred research objectives.

3.3.1 Techno-economic assessments

The TEA, through process simulations and economic modelling, helped establish the requisites for the technical and economic viability of the cassava waste biorefineries. Process simulations in Aspen Plus® v.8.8 software facilitate the requisite equipment, mass and energy balance data for the economic assessment [applicable to **Specific objectives 2 & 3** (section 1.3)**]** [57]. Hence, the technical feasibility of the CWB was assessed through process flowsheet simulations in Aspen Plus® using laboratory data reports on mass conversions (detailed in Chapters 5 & 6). Specifically, the process simulations were developed based on experimentally proven protocols and outcomes for the production of the targeted products using the cassava residues (Table 3.1), thus, ensuring reliability of the resultant technical and economic projections. The reliability of the outcomes is vital for advancing investor confidence and successful uptake of the cassava industries in South Africa. The economic feasibility was evaluated relative to the following economic indicators: (i) minimum expected selling prices of the products (MESP), (ii) Net Present Value (NPV), and (iii) Internal Rate of Return (IRR), which were based on the year 2018 fiscal conditions for South Africa. The MESP, NPV, and IRR have been considered due to their potentials to project the profitability of the CWBs relative to the current market or investment conditions [54]. Investment risks were also assessed through sensitivity analysis, which involved assessments of the profitability impacts by changes [± 25%- advanced biorefineries; ± 50%- waste resource recoveries [185]) in essential economic parameters (capital investments, working capital, total production cost, product prices, feedstock costs and enzyme costs).

3.3.2 Life cycle sustainability assessments

The LCSA [eLCA + LCC + sLCA] helps in identifying opportunities for improvements in the environmental burdens (eLCA), costs (LCC) and socio-economic (sLCA) impacts of the hypothesized CWBs [applicable to **Specific objective 4** (section 1.3)]. It is worth mentioning that the primary objective of the LCSA was to develop a Percentage Sustainability Index (PSI) tool custom-built for decision making regarding sustainable CWB choice from an investor or mutual investor-environmentalist stakeholder's perspective (detailed in Chapter 7). Therefore, the CWB's investment/profitability and environmental savings potential relative to avoided environmental burdens from fossil equivalent products were prioritized in the PSI for the targeted stakeholders (detailed in Chapter 7). Considering the water & pollution burdens, and high carbon footprints associated with the current waste management schemes in the cassava starch industries (section 3.2.2), the LCSA for the CWBs were compared to the current wastes management. Accordingly, the eLCA was focused on comparative analysis of related environmental metrics for the CWBs vs. current management schemes, which includes the global warming potential (GWP), freshwater eutrophication potential (FEP), freshwater ecotoxicity potential (FETP), terrestrial acidification potential (TAP), terrestrial ecotoxicity potential (TETP), and fossil resource scarcity potential (FRSP). The eLCA and LCSA were based on simulations in SimaPro v.9.0.0.49 software (detailed in Chapter 7), which has an extensive database on the environmental inventories for several industrial operations, as well as possibility for user defined inputs for unique processes not found in the database [186]. Relative to the PSI's objective of informing investment decisions (priority of investment/profitability), the LCC was evaluated as the capital investments, production costs, and NPVs, which were obtained from the TEA (section 3.3.1) (Fig. 3-2). The sLCA established the socio-economic impacts in terms of direct and indirect job creation by the CWBs (obtained from the TEA), human toxicity potentials [human health impacts; from the eLCA], and contributions to energy security [surplus electricity generation capacities; from the TEA] (detailed in Chapter 7).

3.4 Justification for the research approach

Several sustainability assessments for biorefinery or bioenergy projects have been focused on techno-economic assessment (TEA), or environmental Life Cycle Assessment (eLCA) (detailed in section 2.6) [47,54]. However, relevant to the objectives of this study, i.e. facilitating implementation decisions by an investor or mutual investor-environmentalist stakeholder, each of these approaches has potential drawbacks that could relatively lessen the benefits or accuracy of the findings for the targeted stakeholders. The drawbacks of the eLCA approach lies in the limitations of the SimaPro software including the lack of extensive database for biorefinery/bioprocess technologies, whereas for the TEA is the unavailability of environmental database in the Aspen Plus software. With respect to the strengths of the eLCA approach, the SimaPro software is well established and has a comprehensive database for the considered environmental inventories and metrics [GWP, FEP, FETP, TAP, TETP, FRSP (section 3.3.2)] [64], while for the Aspen Plus software is its ability to simulate the biorefinery/bioprocess operations through an extensive in-built database process technologies [47,54,57]. The proposed PSI tool, which is based on the principles of LCSA modelling, therefore integrates the TEA and eLCA, as well as related socio-economic impacts of the biorefineries for holistic decision making by the referred stakeholders. The techno-economic assessments (Aspen Plus simulations) provide reliable process and economic data for the eLCA (SimaPro simulations) and PSI tool respectively (Fig. 3-2). Therefore, the considered sustainability assessments approach and methodologies, involving the integration of TEA, LCA, and LCSA (i.e. PSI tool) (Fig. 3-2), help to complement each approach's limitations with the strength of the other.

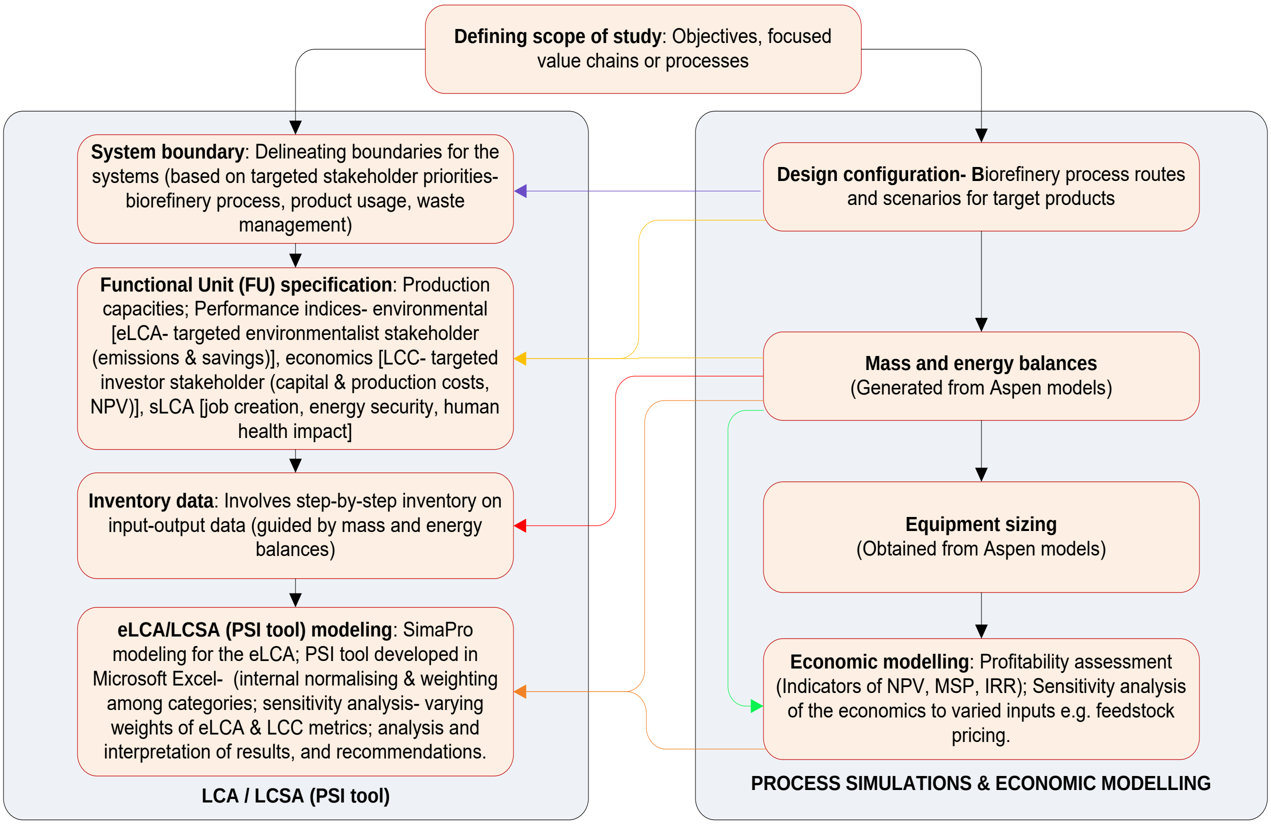

Fig. 3-2: Conceptual approach to the study. In the figure, LCC-Life Cycle Costing, PSI- Percentage Sustainability Index tool (designed specifically for implementation decisions by investor or mutual investor-environmentalist stakeholder), NPV- net present value, IRR- internal rate of return, MSP- minimum expected product price, eLCA- environmental life cycle assessments, LCSA- life cycle sustainability assessments.

4 Estimating the bioenergy potential in integrated residue based biogas or bioethanol and starch production systems for advancing development of agricultural bio-economies

Chapter summary

The establishment of a cassava crop as a sustainable food and energy security crop for South Africa calls for feasibility assessments for the co-production of the food and bioenergy in a sustainable manner. To this end, integration of the starch (food) and residues-based bioenergy production is a foreseeably feasible scheme. Establishing the production potential for cassava versus the established starch crops is essential for the selection of a more beneficial feedstock for integrated starch-bioenergy systems (Specific Objective 1, section 1.3). This Chapter presents the comparative production potential and benefits using multi-criteria analysis (MCA). The considered starch crops and residues are: (i) cassava (stalks + peels), (ii) maize (stover + cobs), (iii) potato (peels), (iv) wheat (straws + chaff), (v) millet (stalks), (vi) sorghum (straws + shells). The considered criteria include: (i) theoretical biogas yield, (ii) theoretical bioethanol yield, (iii) commercial starch yield, (iv) ability to supply and meet energy demand for the starch processes and generate surplus electricity using the biogas, (v) gross revenue contributions of the residue-bioenergy to the respective starch industry, (vi) total gross revenues from the starch industry + bioenergy. The results of the MCA showed that the projected best-to-least starch crop was cassava, maize, sorghum, wheat/potato and millet with respect to the production potential for an integrated starch-bioenergy systems. The findings contribute to knowledge on sustainable value-chains for starch crop resources.

Part of the Chapter 4 has been published as a book chapter*:*

Padi RK*, Chimphango A, 2020. Postharvest technology for advancing sustainable bioenergy production for food processing and reduction of postharvest losses. In: Charis M. Galanakis, editor. Food losses, sustainable postharvest and food technology, Elsevier (In press).*

Declaration by the candidate:

With regard to Chapter 4, pg. 53-88, the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution
Definition of scope of study, conception of the approach & metrics for comparing the residues-bioenergy/starch production systems, analysis and interpretation of results, writing of the manuscript.	85%

The following co-authors have contributed to Chapter 4, pg. 53-88:

Name	E-mail address	Nature of contribution	Extent of contribution
Chimphango, A.	achimpha@sun.ac.za	Contributed to the project scope definition, assisted with suggestions, general discussions, review and proof-reading of manuscript.	10%
Roskilly, A.P.	anthony.p.roskilly@durham.ac.uk	General discussions and review of manuscript	5%

Signature of candidate: ………………

Date: ………………………………..

Declaration by co-authors:

The undersigned hereby confirm that:

1. The declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 4, pg. 53-88

2. No other authors contributed to Chapter 4, pg. 53-88, besides those specified above, and

3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 4, pg. 53-88, of this dissertation.

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Estimating the bioenergy potential in integrated residue based biogas or bioethanol and starch production systems for advancing development of agricultural bio-economies

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Abstract

High energy costs lead to under utilization and postharvest losses of starch crops, such as cassava, potato, maize, wheat, millet and sorghum in developing countries. The total use of starch crops (main crop and residues) has potential for high-value food and non-food applications. For instance, the starch from root tubers (e.g. cassava) have various industrial uses, including pharmaceuticals and food derivative (e.g. glucose syrup) products, while the crop residues (e.g. stalks) have potential for bioenergy (e.g. biogas, bioethanol) production. Thus, integrating crop residues and bioenergy in starch production is a foreseeable sustainable biorefinery approach for advancing industrialization of starch crops. However, knowledge gaps in relation to socio-economic benefits from an integrated biorefineries approach exist, which hamper investment decisions. In this paper, the potential of different scenarios for integrated biorefineries (starch-bioenergy systems) to advance industrialization of the starch crops are assessed using a multi-criteria analysis (MCA) framework, so that the crops' potential can be ranked. The bioenergy-starch biorefinery scenarios involve production of starch from selected starch crops and biogas or bioethanol from the associated residues. The selected crops are (i) cassava (stalks + peels), (ii) maize (stover + cobs), (iii) potato (peels), (iv) wheat (straws + chaff), (v) millet (stalks), (vi) sorghum (straws + shells). The multi-criteria used to assess the crop potential included (i) theoretical biogas yield, (ii) theoretical bioethanol yield, (iii) commercial starch yield, (iv) ability to supply and meet energy demand for the starch processes and generate surplus electricity using the biogas, (v) gross revenue contributions of the residue-bioenergy to the respective starch industry, (vi) total gross revenues from the starch industry + bioenergy. The biofuels and starch production potential were estimated using technical mass conversions relative to crop yields/composition data, which were then used to evaluate associated gross revenues using market prices. The results of the MCA showed that the projected best-to-least starch crop was cassava, maize, sorghum, wheat/potato and millet with respect to the potential for an integrated starch-bioenergy systems. Compared to cassava, both maize and potato showed higher biogas (2324 m^3 versus 1656 m^3 CH_4/ha per annum) and starch production potential (8.24 t/ha versus 3.28 t/ha per annum) respectively. However, cassava showed greater bioethanol production potential than maize (1739 L/ha versus 1212 L/ha per annum). The bioenergy could contribute considerably to gross revenues of starch industries, reaching 11-44% and 17-51% for millet and sorghum respectively. Conversion of residues from all the crops into biogas and then electricity, has potential to meet the energy needs of the starch processes and can generate surplus electricity (397-4973 kWh/ha). Therefore, the potential energy self-sufficiency in starch industries, realized through biogas conversion of field and process residues, could advance industrialization of under utilized starch crops with socio-economic and environmental benefits.

Keywords: Bio-economies; Bioenergy; Biomass residues; Integrated starch-bioenergy production; Starch crops; Sustainable developments

4.1 Introduction

High post-harvest losses contribute to food insecurity in developing regions [36]. According to Hodges et al. [187], post-harvest losses in the developed regions are largely due to expired or discarded food. Conversely, spoilage due to inadequate post-harvest agricultural systems, including the lack of processing to storable forms, represents the main cause of food losses in the developing regions [187]. The latter highly impacts easily perishable staples, including starch grains and root tubers. For instance, post-harvest losses for maize and sorghum totaling 17.5% and 11.8% of annual productions (respectively) have been estimated for Eastern and Southern Africa [187]. Starch agro-processing activities in these developing regions are mostly limited to small scale traditional processes, characterized by inefficient mass and energy conversions, laborious operations, and capacity limitations, leading to under utilization of starch crops [21]. Therefore, mechanization improvements are required for industriialising the starch processing sector in order to reduce postharvest losses and obtain full economic potential from the crop.

Industrial starch extraction is one of the postharvest processes that is energy-intensive. Thermal energy and electricity consumption of 1600-2500 MJ and 170-250 kWh per ton for cassava starch production have been reported [38]. The drying stage has been identified as the most energy-intensive operation for various starch processes [37]. For example, in cassava starch facilities, estimates show that drying energy accounts for 69% of the total starch production energy of 2008 $MJ.t^{-1}$ [39]. The prevalence of unreliable energy supply, particularly in most developing countries in sub-Saharan Africa (SSA), is a foreseeable risk to cassava starch industrialization [40,42,188]. Furthermore, in the energy deprived countries, there is escalation or high volatility of energy prices, which negatively impacts on starch industries' global competitiveness [23,43]. For instance, energy contribution to cassava starch processes in places such as Thailand constitutes approximately 14% of production cost [44], whereas, for similar processes in Nigeria, the energy contribution to the production cost ranges from 20–25% [12]. The disparity in production energy cost between the two countries signifies the importance of access to affordable and reliable energy. Energy is, therefore, considered to be a catalyst of economic sustainability for agricultural based industries in impoverished communities.

One way to achieve affordable and sustainable energy supply for starch processes is through the use of biomass residues from the starch crops generated both in the field and at processing plants, which when converted can generate bioenergy for use in the agro-processing operations. Such measures could promote sustainable industrial development of the under utilized starch crops in impoverished communities and advance the circular bioeconomy. Furthermore, the use of bioenergy will help mitigate environmental impacts associated with the current use of fossil fuels and disposal of the residues, thereby reducing the net environmental impact of agro-industries.

Comparative studies on cultivation efficiencies for starch crops have been extensively studied (Table 4.1). However, little has been done to compare the bioenergy production potential (biogas or bioethanol) from the residues in starch crops processing systems. Such holistic assessments are deemed essential in identifying promising feedstock for integrated biorefineries in which food, bioenergy and other high value bioproducts can be produced. In a study by Jekayinfa and Schol [189], annual bio-heat or bioelectricity generation potential, collectively, for available cassava peels, millet stover, maize stover, and sorghum straw were estimated for Nigeria. Other studies, Kemausuor et al. [190], investigated the sustainable bioethanol and biogas production potential from available agricultural and forest residues and municipal wastes in Ghana. However, some studies have estimated the annual bioenergy potential (cellulosic ethanol) for major crop residues including cassava stalks and peels, maize stalks and cobs. Some of these studies have been done in Africa using estimated sub-regional residue potential [110]. In all the referred studies, the authors aimed at establishing annual biofuel or bioenergy production potential for collective crop residues or biomass waste, thus limiting comparison of the bioenergy production potential amongst crops, which is necessary to design postharvest processes for integrated biorefineries. Mwithiga [191] estimated cellulosic ethanol production from maize stover, wheat stalks, and sorghum stalks for South Africa at 142, 143 and 138 L/ha respectively. However, the evaluation by Mwithiga [191] was limited because it was based on field residues only.

Table 4.1: Comparative cultivation performance of selected starch crops

Crop	**Maximum recorded yield (t/ha) [a]**	**Daily energy production (kJ/ha) [a]**	**Total cultivation biomass [dry mass (g) per kg water]**	**Yield [dry mass (g) per kg water]**	**Starch content, % of grain or tuber, dry basis**
Cassava (*Manihot esculenta*) *	71	1045	2.9 [b]	1.7 (HI 60%) [b]	81.4 [c]
Sweet potato (*Ipomoea batatas*) *	65	752	NA	NA	52.54 [d]
Maize (*Zea mays*) **	20	836	NA	NA	70 - 75 [e]
Sorghum (Sorghum bicolor) **	13	477	3.1 [b]	1.2 (HI 40%) [b]	60 - 65 [e]
Wheat (Triticum aestivum) **	12	460	NA	NA	57 - 75 [e]

* fresh harvest; ** dry product; N/A: not available; [a] [13]; [b] [14]; [c] [68]; [d] [192]; [e] [16]; HI: harvest index = (weight of dry grain or tuber/total dry weight) x 100

This study therefore investigated bioenergy potential for primary biomass residues of widely cultivated starch crops, including cassava (stalks + peels), maize (stover + cobs), potato (peels), wheat (straws + chaff), millet (stalks), and sorghum (straws + shells), to conduct a holistic comparative benefit assessment. Specifically, residues-based power and transport fuel production capacities through biogas and cellulosic ethanol conversions, respectively, have been considered. The projections were based on technical mass conversions vis-à-vis crop yields and composition data. Furthermore, ranking of the starch crops, regarding the possibility to implement integrated starch-bioenergy biorefineries is extremely important. The ranking was conducted using multi-criteria analysis (MCA) framework based on the following criteria:

(i) theoretical biogas yield, (ii) theoretical bioethanol yield, (iii) commercial starch yield, (iv) ability to supply and meet energy demand for the starch production process and generate surplus electricity using the biogas, (v) gross revenue contributions of the residue-bioenergy to the respective starch industry, (vi) total gross revenues from the starch industry + bioenergy. The developed starch crops and cassava cultivation backgrounds of South Africa and Ghana respectively [32,187] were used as a model scenario to extend the usefulness of the findings.

4.2 Production of starch crops and potential for cassava in South Africa

Annual production and yields of major starch crops grown in South Africa are shown in Fig. 4-1, with the exception of the data for cassava yields that are shown for Ghana (Fig. 4-1b), which is presented to facilitate comparison since cassava production is marginal and there is no reported data for South Africa. Maize leads the production with an average output of 8.7 million t/a, followed by wheat (1.8 million t/a) and potato (1.2 million t/a) (Fig. 4-1a). Comparing the yields (on a fresh weight basis), cassava yields are higher than maize, wheat and sweet potato (Fig. 4-1b), but seemingly lower than that of potato (maximum of 20 t/ha versus 35 t/ha, Fig. 4-1b). However, the cassava yields may be comparable to potato under improved conditions of cultivation inputs and practices. For example, a study [193] on smallholder farms in Gabon revealed the adoption of inept farming techniques, pests/disease burdens, and the lack of improved yielding varieties resulted in low yields below 8 t/ha. Conversely, a turnaround was achieved with high-yielding disease-resistant varieties, improved cultivation practices, such as planting in rows (optimizing planting densities) and avoidance of cultivation in waterlogged soils (preventing rots), resulting in the improvement in yields (up to 30 t/ha). Similar turnarounds have been reported for Kenya and Uganda, with cited increases of up to 140% from base yields of 8.6 t/ha [194].

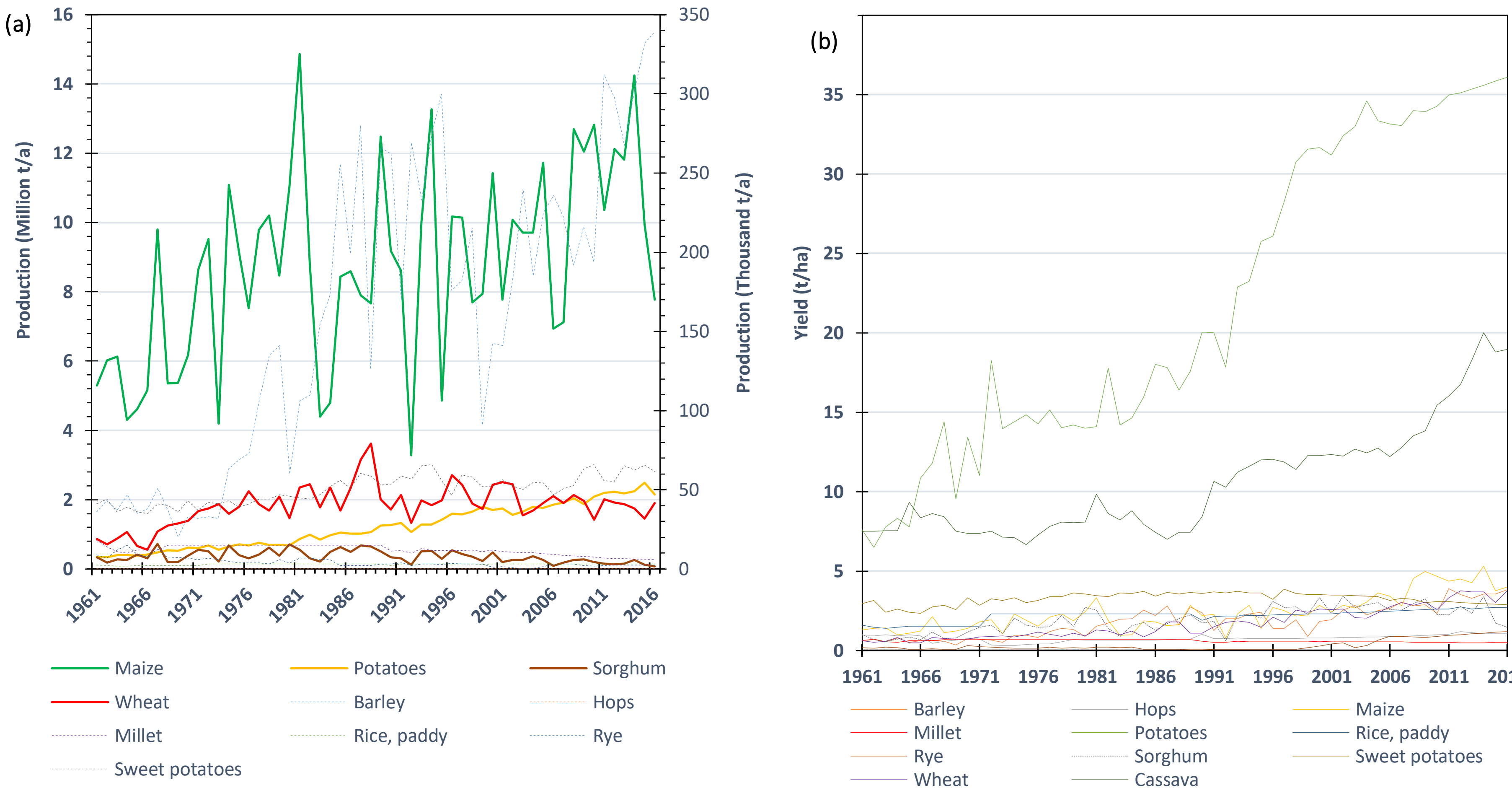

Fig. 4-1: Annual production capacities of selected major starch crops in South Africa; With the exception of Maize, Potatoes, Sorghum and Wheat (with higher magnitudes, millions) plotted on the left vertical axis, all other crops with lower magnitudes of productions (thousands) are plotted on the right vertical axis for ease ofy readability (Source data: [5]); b) Cultivation yields of major starch crops in South Africa, with the exception of cassava (which is for Ghana); Data on cassava yields for Ghana is presented solely to facilitate comparison as no data on cassava production for South Africa was reported for the period 1961 – 2016 (Source data: [5]).

4.2.1 Primary biomass residues from selected starch crops and existing uses

In relation to starch root crops, peels have been suggested as sustainable source for biogas or bioethanol production [190,195] for crops such as potatoes. However, the stalks and discarded potatoes could be used as feedstock for bioenergy. In case of cassava, the woody stems (stalks) are often left in the field (field residues) after root harvesting [11]. Average production of stalks has been estimated at 51% the mass of the cassava roots [100], thus, large amounts are generated. Small fractions of the generated stalks are used as planting materials, constituting approximately 10-20% of the total mass generated [32]. The use of stalks as low heating value fuel in some African countries has been cited [11]. The starch composition of the stalks has been established to be 22-39% of the dry matter, which has inspired interest for biofuel applications in recent years [11,100]. Similar to potatoes, cassava starch processes generate peel and is estimated to be 10-20% of the root mass [83,84], and typically consists of cellulose (37.9%), hemicellulose (37.0%) and lignin (7.5%) [85]. Reports indicate that approximately 68% of the generated cassava peel is used as livestock feed in some areas in Nigeria [86,196]. Furthermore, practices of burning, landfilling, or open discarding large portions of the peels, have consequential air and land pollutions, has been cited [83].

Generally, for maize, the cobs represent the primary process residues, while the stover (stalk + husks) represent the field residues. Usage of the cobs as low heating value fuel is common in most developing regions, which could be as high as 35% of the generated residue [86,196]. It has been estimated that about 2 t/ha of maize stover or wheat straws are left on farms to control soil erosion and soil carbon contents, while 14% of the residuals are used in livestock farming as feed and bedding [197]. Relevant to potato, only the peel (process residue) has been suggested as sustainable source for biogas or bioethanol production [190,195].

Hence, biomass residues generated from the primary processing of the starch crops could be considered as feedstock for sustainable bioenergy production as reported in other studies.

This includes stalks and peel from cassava, stover and cobs from maize, potato peel, wheat straw and chaff, millet stalks, and sorghum straw and husks [190,198].

4.3 Residues-based bioethanol and biogas production

4.3.1 Bioethanol

Biochemical conversion of sugar, starch and lignocellulosic substrates to bioethanol is well established. The complexity of the conversion process is dependent on the molecular structure of the substrates [11], as shown in Fig. 4-2a,b. Sugar substrates (e.g. sugarcane juice) are directly fermented into bioethanol by microorganisms such as yeast [199]. Starch substrates (e.g. corn) require hydrolysis of the starch into sugars for subsequent fermentation to bioethanol, usually achieved using enzymes and yeast respectively [51]. Lignocellulosic biomass (e.g. maize stover) is first pre-treated to facilitate the breaking down, through enzymatic hydrolysis, of cellulose and/or hemicellulose components into reducing sugars, followed by fermentation (see Fig. 4-2b) [200,201].

In bioethanol production process, enzymatic separate hydrolysis and fermentation (SHF) or simultaneous saccharification and fermentation (SSF) can be carried out. During SHF, the enzymatic hydrolysis and fermentation stages are performed in separate vessels with the associated advantage of potentially achieving optimal process conditions of temperature and pH for each stage [202]. The limitations in SHF are mainly due to product accumulation (glucose and cellobiose), which inhibits enzyme (cellulase) activity during the hydrolysis stage [203,204]. On the other hand, SSF combines enzymatic hydrolysis and fermentation stages in the same vessel, which ensures direct conversion of the glucose released, by cellulase activity through ethanologenic microorganisms such as yeast, to ethanol. Thus, SSF overcomes the inhibition of cellulase activity by the accumulated glucose, as is the case in the SHF approach [205]. Furthermore, the ethanol produced by SSF provides a sanitization effect on the broth medium, which eliminates contamination. The ethanol sanitization effect is attributed to the increased saccharification rate by desired microorganisms, thereby improving ethanol productivity for the SSF approach, which is not the case for the SHF approach [206].

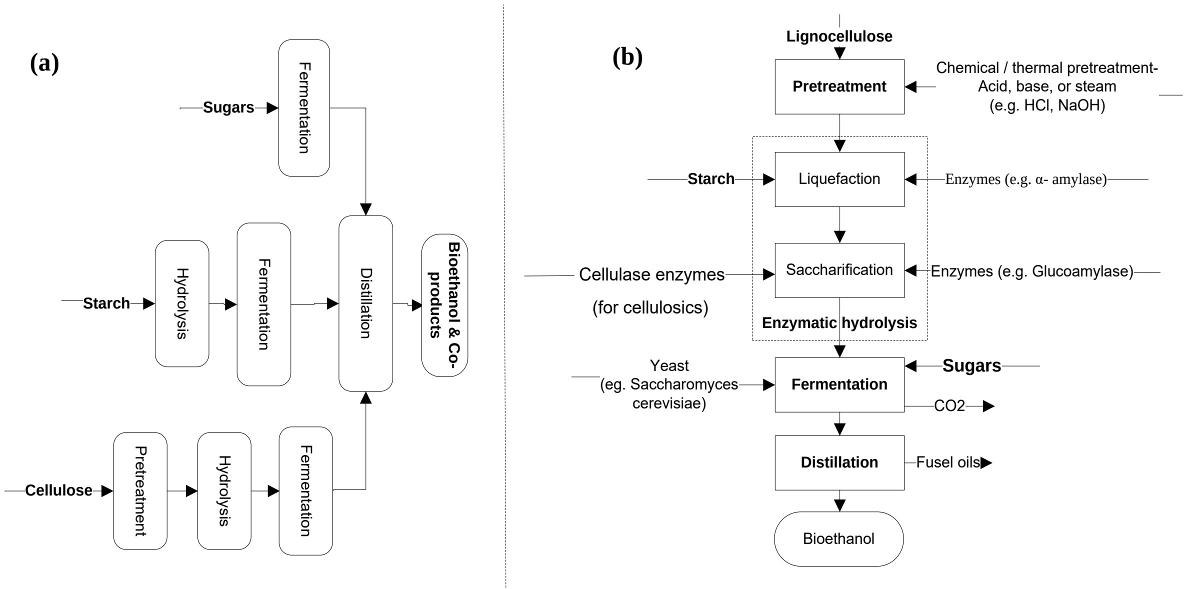

Fig. 4-2: Bioethanol process path for various substrates, (a) Presents the key unit operations; (b) Shows typical inputs and outputs from the process.

The lignocellulosic and starch biomass residues from cultivation or processing of starch crops, therefore, offer great opportunities for bioethanol production. Various experimental work has demonstrated the technical feasibility or optimal processes for bioethanol conversions using these residues and these are summarised in Table 4.2.

Table 4.2: Selected experimental work on bioethanol production from lignocellulosic starch crop residues

Residue type	Pre-treatment conditions	Hydrolysis conditions	Sugar yields	Fermentation conditions	Product yields	Reference
Corn stover	NA	Pulverised stover + 200g 65–80% H_2SO_4 solution (1:1 weight ratio)	Hydrolysate composition- ~ 3.5 g/L cellobiose; ~29 g/L glucose, ~ 25 g/L xylose, ~ 8.5 g/L arabinose, ~5.0 g/L galactose	S. cerevisiae strains KF7 (cell conc. of ~0.45x10^8/mL) and NAPX37 (cell conc. of ~0.15x10^8/mL), 24h	Ethanol conc. of 13g/L (for KF7); 19 g/L (for NAPX3)	[207]
Wheat straw	Extrusion in a twin-screw extruder, 50–150 °C, 125-140 rpm, NaOH/straw (7.3)	Celluclast 1.5L (16%/DM) + Cellobiose N188 (4%/DM)	Glucose yield- 73g/100g glucan in pre-treated material	NA	NA	[208]
Cassava peels	NA	0.2 g solids, 10 ml 0.2 M acetate buffer + water (2:3), 5 % (v/w) cellulase + 10 % (v/w) beta-glucanase, 50 °C, up to 120h	Glucose conc. of 3.97 g/l, 11.58 g/l, and 14.67 g/l at 4h, 24h and 120 h resp.	NA	NA	[209]
Millet stalk	20 g substrate + water (15% w/v) + 200 ml 1M HCl saturated with lithium chloride, 27°C, 1h.	Washed pre-treated material + 0.4% w/v Trichoderma viride cellulase MVA 1284 (0.5% w/v)	16.4% hydrolysis products	NA	NA	[210]
	NA	0.75g substrate + 5 ml of 4M HCl saturated in lithium chloride and incubated (50°C, l h), followed by water dilution (0.5 ml water) and hydrolysis (100°C, 45-60 s).	79.2% hydrolysis products	NA	NA	[210]
Cassava Stalks	1.5 g stalks + 100 ml 0.1 M H_2SO_4, 120-135°C, 10-90 mins.	250ml Sumitime C [cellulase (20 FPU.g^{-1} substrate) + α-amylase (100 U.g^{-1} substrate) + amyloglucosidase (100 U.g^{-1} substrate) + xylanase (500 U.g^{-1} substrate) + pectinase (250 U.g^{-1} substrate)], 50°C, 48 h.	Pre-treatment at 135°C, 10 min- 5.71g/L glucose + 7.91 g/L reducing sugars; at 60 mins- 9.36g/L glucose + 12.67 g/L reducing sugars.	Highest sugar hydrolysate + 5% v/v S. cerevisiae KM1195, 30°C, 18h; Both SHF and SSF investigated	Ethanol yield, concentration & production rate: 0.502 g (g-total sugar)$^{-1}$, 6.23 g.L^{-1}, 0.593 g. (L.h)$^{-1}$ resp.	[211]

NA: not available; DM: dry mass

4.3.2 Biogas production

Biogas, a fuel with a typical composition of 64 % v/v CH_4, 36 % v/v CO_2 and 670-2500 ppmv H_2S [212], is produced by microbial degradation of biomass through anaerobic digestion (AD). AD technology is well established and has been extensively discussed in literature [45,213]. AD has an advantage over thermochemical processes, such as combustion, pyrolysis and gasification, because energy can be recovered from organic waste materials characterized with high moisture content more efficiently and with reduced environmental burdens than the counterparts, as demonstrated by Fredriksson et al. [214]. In addition, a by-product of the AD process, a nutrient-rich digestate that contain nitrogen and phosphorous, has shown benefits as an organic fertilizer for farming [71,214]. Therefore, AD is a potential environmentally sustainable treatment option for recovering energy from wastewater and biomass residues generated from starch extraction processes. For instance, nearly 90% of cassava starch factories in Thailand reportedly use AD systems to produce biogas from the associated wastewater and lignocellulosic residues (bagasse) for process energy needs [72].

Similar to other fermentation processes, recalcitrance of lignocellulosic substrates to microbial degradation is one of the major drawbacks in AD [45,198]. Therefore, pre-treatment of lignocellulosic substrates using either physical methods (comminution, extrusion, steam-explosion, liquid hot water, and irradiation) or chemical methods (alkaline, acid, catalyzed steam-explosion), increases biogas yields in the AD process [45,215]. However, compatibility of a pre-treatment method with a particular substrate must be experimentally determined as some substrates have shown detrimental response to acid pre-treatment. For instance, a study on pre-treatment of rapeseed, sunflower meals and straws using 2 wt.% H_2SO_4 (at 121°C for 1 h) reported an adverse effect on methane production for all the studied substrates [216]. Likewise, $C_4H_4O_4$ pre-treatment of bracken, hay and straw showed positive effect on biogas yield for bracken but the contrary was noted for hay and straw [217]. One contributing factor to the low biogas yields is the formation of inhibitors such as hydroxymethylfurfural (HMF) and furfural in higher concentrations during acid pre-treatment, which inhibits microbial activities, thus, limiting methane production [215]. The high concentrations of inhibitors could however be minimized under optimal conditions of temperature, pH and exposure time. Optimization experiments to determine optimal process conditions have proven useful in this regard [198,207,215]. An extensive review on pre-treatment approaches and impacts on biogas yields for lignocellulosic substrates can be found in available literature [45,215].

The impacts of temperature, pH and the carbon-nitrogen ratio (C/N) of the substrate on the efficiency of AD processes have been studied [213]. For instance, the recalcitrance of cassava peel to microbial degradation in AD processes due to the high carbon-nitrogen ratio (C/N of 48.7), and resultant low biogas yield (0.6 l/kg-TS) have been reported [218]. Co-digestion of substrates with high C/N and animal manures have shown to increase biogas yields relative to yields from the individual feedstock, which is derived from nutrient balance for efficient microbial activity [219,220]. Optimisation of such co-digestion systems has been investigated for some lignocellulosic residues. For instance, Adelekan [218] found mixing ratios of 1:1 weight proportions of pig manure and cassava peel to be optimal for co-digestion to biogas.

4.4 Estimation of primary residue-based biofuel capacities and derived benefits to industrial developments

4.4.1 Conceptual approach

This section describes an approach to estimating the capacities for the primary residue-based power and transport fuels through biogas or bioethanol conversions respectively. The potential benefits of biofuels to the industrial development of the starch crops were also examined. The conceptual approach involved estimations of generated primary residues, which were then used to compute the biogas or cellulosic ethanol production potential. The biogas and bioethanol production potentials were then used to estimate power generation and transport fuel production potential respectively. The corresponding crops were considered as feedstock for commercial starch production, thus, starch capacities for the crops were assessed based on literature. The estimated biogas, bioethanol, and starch capacities were then used to evaluate the associated gross revenues. Furthermore, comparative benefits of the residues-bioenergy to the starch industries were assessed using multi-criteria analysis (detailed in section 4.1) and the findings were used to rank the crops in relation to the potential to design integrated starch-bioenergy biorefineries (detailed in section 4.5.5). Specific details of the approach used to conduct the estimations and analysis are presented as follows.

4.4.2 Estimating available primary biomass residues

Sustainable removal of field biomass residues from the farms is reliant on climatic conditions and crop management practices due to consequential impacts on soil erosion, N_2O emissions from farm soils, and soil organic carbon turnover [157]. Estimation methods found adequate for primary agricultural residue generation includes theoretical and technical estimates [190]. The theoretical potential simply entails all residues generated and is estimated based on crop production data, while the technical potential refers to the fractions of the theoretical estimate that are technically recoverable [190]. The technical estimates account for the social (alternate uses) and environmental limiting factors for recoverable biomass [190], thus, the sustainable biomass supply. The theoretical potential is estimated by multiplying the crop production by a factor, termed residue to product ratio (RPR), which is estimated based on regional farming conditions, such as crop yields and physiological compositions. The technical potential is then calculated by multiplying the theoretical potential by a recoverability fraction (RF) [221]. The RF, defined as the ratio of technically (sustainably) retrievable residues to the theoretical potential, is estimated based on crop and soil type, climatic conditions and cropping system, as well as competitive uses of the biomass [197,222]. Thus, the theoretical and technical estimates were considered as the maximum and minimum (sustainable) residue potentials, respectively, in this study.

The RPR, RF, and crop production data presented in Table 4.3 were used to estimate the theoretical and technical residue potentials. To allow for comparison amongst crops, residue potentials were estimated on a per hectare cultivation and per annum basis using average yields (t/ha) and average annual production (million t/a) data respectively for South Africa (detailed in Table 4.3). In the estimations, residues with no reported data on RPR and RF for the South African context were estimated based on reports elsewhere, as detailed in Table 4.3. For production and yield data for cassava, a conservative assumption of the capacities for Ghana (third leading producer in Africa) has been considered (Table 4.3).

Table 4.3: Crop data and parameters for estimating primary residue potentials for South Africa

Crop	**Crop production**		**Residue**	**Residue to product ratio (RPR)**	**Recoverability factor (RF)**
	t/ha	**Million t/a**		**t/t $_{crop}$**	**t/t $_{theoretical}$**
Cassava	16.1 [a]	14.49 [a]	Stalks *	0.06 [c]	0.8 [c]
			Peels **	0.25 [c]	0.2 [c]
Maize	4.2 [b]	10.72 [b]	Stover *	1.28 [d]	0.54 [e]
			Cobs **	0.29 [f]	0.86 [h]
Potato	34.6 [b]	2.11 [b]	Peels **	0.1 [g]	0.86 [h]
Wheat	3.2 [b]	1.85 [b]	Straw *	1.3 [i]	0.32 [e]
			Chaff **	0.41 [j]	0.86 [h]
Millet	0.51 [b]	0.0073 [b]	Stalks *	1.83 [k]	0.8 [k]
Sorghum	2.50 [b]	0.17 [b]	Straw *	1.99 [k]	0.8 [k]
			Shells **	0.41 [k]	0.86 [h]

[a] From a conservative outlook on the intensification program of cassava in South Africa, it was assumed that production could reach similar capacities of Ghana (third leading producer in Africa), thus average annual production/yield for Ghana (2006-2016) were assumed; [b] To account for instability in productions and yields, average annual production/yields from 2006-2016 were considered [5]; [c] Adopted from a similar study [223], which also factors stalk requirement as cultivar or planting materials; [d] Average of reported RPR for maize yield of 5 t/ha [197]; [e] Estimated based on assumption of 2 tons per hectare of theoretical potential required on farms to ensure soil carbon content and mitigation of soil erosion, while 14 % of the remaining theoretical potentials is used in livestock farming as feed/bedding[197]; [f] Average of values reported [223,224]; [g] Adopted from a similar study [195]; [h] Estimated based on assumption that 14% of theoretical potential used in animal farming/heating fuel for cooking purposes, based on reports by Valk [197]; [i] Reported RPR for wheat straw in South Africa [191]; [j] Average of reported range [225]; [k] Adopted from a similar study [190]; * & ** denotes field and process residues respectively

4.4.3 Biogas or bioethanol production potential

The corresponding biogas or bioethanol production potential from the theoretical and technical residues were estimated based on the approach by Kemausuor et al. [190]. In their computations, the authors considered technical conversion factors as described in Eq. 4.1 and Eq. 4.2. Furthermore, electricity generation potential from the projected biogas were estimated based on conversion rate of 1 m^3 biogas (at 60 vol.% CH_4 content) to 2 kW electricity for gas-engine generators [226].

$$P_{biogas} = B_{res} \times [(Meth_{glu} \times Glu_{conc}) + (Meth_{hem} \times Hem_{conc})] \times \eta_{proc} \quad (4.1)$$

$$P_{ethanol} = B_{res} \times Glu_{conc} \times Hyd_{yield} \times Eth_{yield} \times \eta_{pret} \times \eta_{enz\ conv} \quad (4.2)$$

Where: P_{biogas} is the biogas production potential (m^3 CH_4/ha); B_{res} is the theoretical or technical biomass residue potential (t/ha); $Meth_{glu}$ and $Meth_{hem}$ are the methane production potential from glucan and hemicellulose respectively, computed using Buswel's formula (m^3 CH_4/t glucan or m^3 CH_4/t hemicellulose); Glu_{conc} is the glucan (cellulose or starch) concentration in residue (t glucan/t TS); Hem_{conc} is the hemicellulose concentration in residue (t hemicellulose/t TS); η_{proc} is the average efficiency of continuous biogas production compared with biomethane production potential (assumed to be 80% for crop residues); $P_{ethanol}$ is the ethanol production potential (t/ha); Hyd_{yield} is the theoretical glucose yield from enzymatic hydrolysis of glucan (1.11 $t_{glucose}/t_{glucan}$); Eth_{yield} is the stoichiometric yield of ethanol from glucose (0.51 $t_{ethanol}/t_{glucose}$); η_{pret} is the efficiency of pre-treatment (glucose conserved) (assumed to be 90%); $\eta_{enz\ conv}$ is the efficiency of enzymatic conversion (cellulose converted) (assumed to be 80%). Additional information provided in Appendix A.1.

4.4.4 Starch extraction process energy demands and product yields

The conventional approach to starch extraction from cereals or grains is the wet milling process, having associated co-products of gluten meal, germ, and gluten feed (Fig. 4-3). The process includes stages of feed handling, steeping, and separation/recoveries of the germ, fibre, gluten feed, and starch. The separation/recoveries include unit operations of washing, evaporation, and drying, thus, the need for thermal drying energy in the form of steam, hot air, or hot combustion gases [38,227,228]. Wet milling starch extraction from root crops is similar to the wet milling process for cereals/grains with the exception of the steeping step, and the germs and gluten co-products. Typical energy (electrical and thermal) consumption for industrial wet milling processes for the considered crops are summarised in Table 4.4.

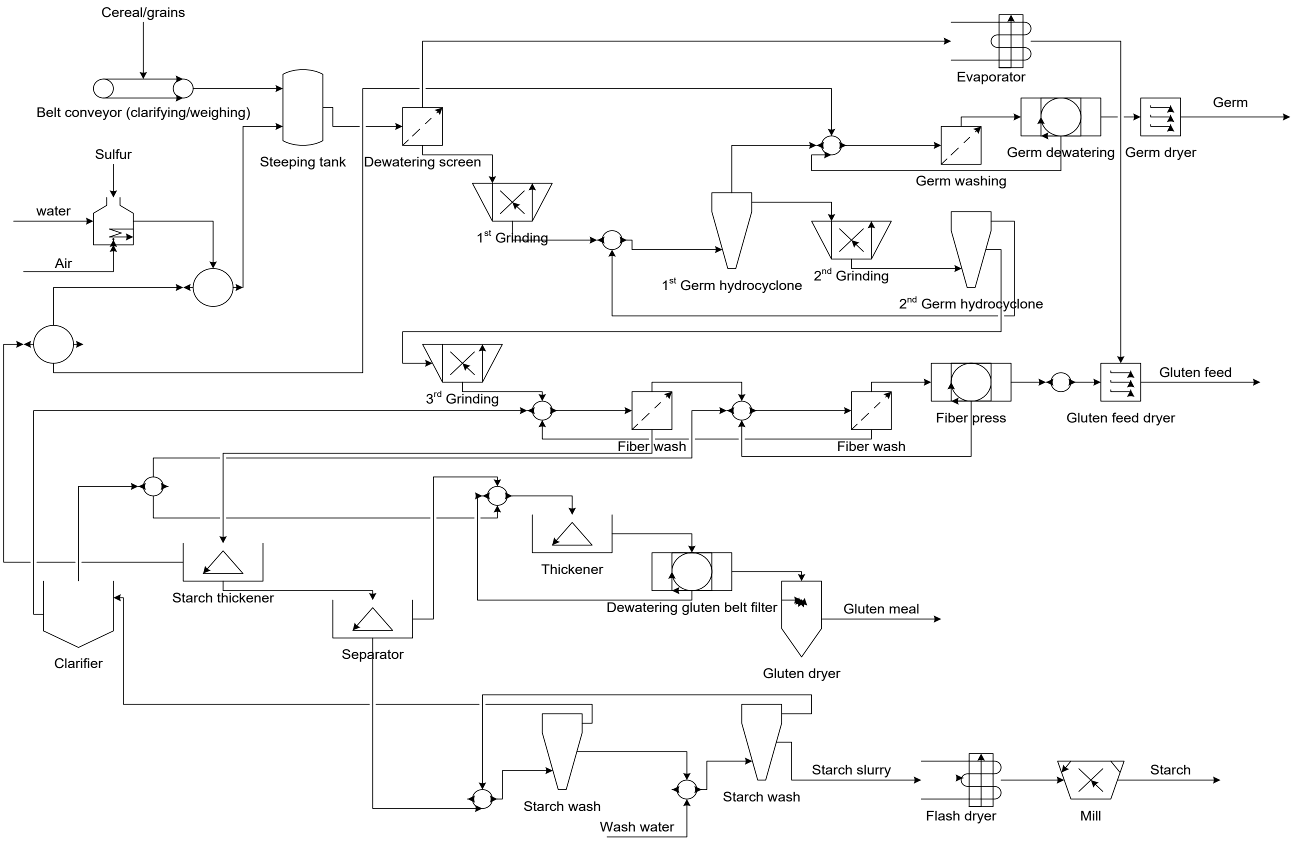

Fig. 4-3: Flow diagram of a wet milling starch extraction process (Adapted from [228])

Table 4.4: Typical energy consumption of starch extraction processes for the considered crops

Feedstock	Process electricity (kWh/ton crop processed)	Process thermal energy/fuel (MJ/ton crop processed)		Comments	Source(s)
Cassava	40.7	Thermal	452.3	Averages of ranges reported for wet milling	[38]
Maize	86.6	Natural gas	1269.0	Maize wet milling process	[228]
Potato	60.0	Diesel	72.8	Averages of ranges reported	[227]
		Natural gas	795.0	Averages of ranges reported	
Wheat	350.3	Natural gas	3780.0	Averages of ranges reported	[227]
Millet	86.6	Natural gas	1269.0	Adopted from maize starch process, based on reports of similarity in wet milling [227]	[227]
Sorghum	86.6	Natural gas	1269.0	Adopted from maize starch process, based on reports of similarity in wet milling [227]	[227]

Commercial starch production capacities for each crop were assessed based on the assumption that all the crops produced per hectare are utilised for starch production, which was to ensure a common basis for comparing the crops. Typical yields of starch and major co-products for the considered crops are presented in Fig. 4-4, which are estimated based on a report by van Zeist et al. [227], with the exception of cassava that is based on accounts by Sriroth et al. [38]. The reported starch yields generally agree with accounts by various authors. Pingmuanglek et al. [39] indicated an average of 4.34 tons cassava yields for 1 ton starch for factories in Thailand. Percentage starch yields per fresh grains (wt.%) of 60.2% and 59.7% for sorghum and maize respectively have been cited [229]. Industrial potato starch processes reportedly produce 175 kg starch per ton of tubers processed [230]. Reported yields for most industrial wheat starch extraction processes ranged from 45-60% of wheat flour weight [231], while flour yields were ~84 wt.% of the grains [232]. Hoover et al. [233] demonstrated millet starch yields of 53-56 wt.% of whole grains. Thus, in the present study, the starch/co-product yield estimates in Fig. 4-4 and the crop production data in Table 4.3 were used to estimate the production capacities of commercial starch/co-products.

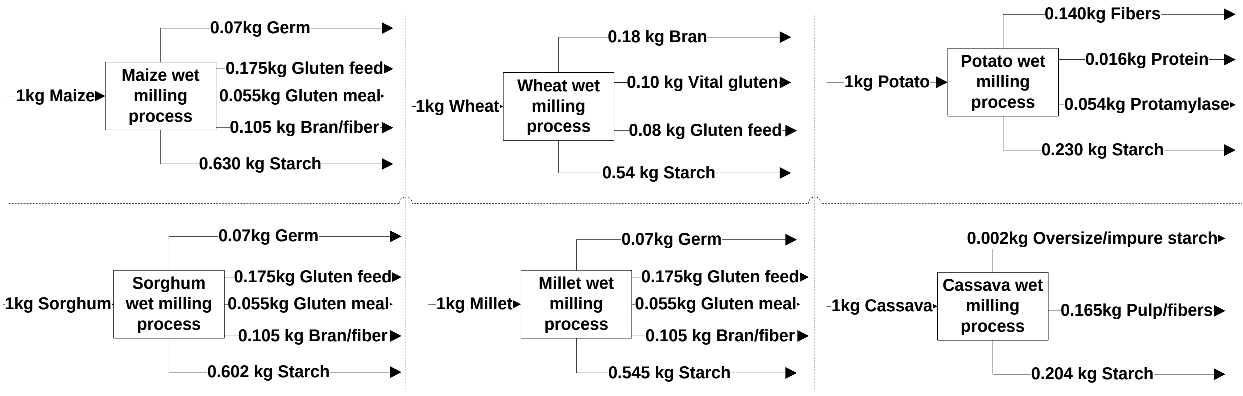

Fig. 4-4: Starch and co-products yields for wet milling processes of the studied crops. Data for maize, sorghum, potato, wheat, and millet are adapted from [227], while that for cassava is based on report by [38] [NB: crop inputs are fresh mass basis].

4.4.5 Gross revenue estimations

Biofuel markets are yet to be regulated in SSA, including South Africa. The gross revenue projections for the biofuels were therefore assumed to be reliant on replaceable energy forms or end-uses. Biogas (with a calorific value of 38.7 MJ/m^3 CH_4) was valued based on the energy equivalence of liquefied petroleum gas- LPG (93.2 MJ/m^3) and average LPG price of \$0.311/m^3 for South Africa [234]. Similarly, bioethanol was valued based on the energy equivalence of petrol (major transport fuel). With calorific values for petrol (30 MJ/L) and bioethanol (21 MJ/L) [235], approximately 1 L of bioethanol is equivalent to 0.7 L of petrol. A petrol price of \$1.13 per litre was used [236]. Apart from the production costs, other major price determinants for native starch and related derivatives are the choice of feedstock, consumer preference, and currency exchange rates [16]. In the revenue estimations, the average price for different starches quotes were used to take account to price variations, which typically ranged from \$0.32-0.40/kg for maize starch, \$0.72-0.86/kg for potato starch, \$0.58/kg for cassava starch, and \$0.94/kg for wheat starch [16]. Prices for sorghum and millet starch were not readily available and were therefore assumed to be same as maize starch due to similarities in prices for grains [237] and the wet-milling process [229,233]. Relative to the maize starch price mentioned in this section, prices for gluten feed/gluten meal, germ/protein and bran/fibre/impure starch co-products were estimated to be \$0.169/kg, \$0.595/kg, and \$0.188/kg respectively [227]. It must be emphasized that the price estimates were based on end-user/retail prices, which were considered due to the lack of data on actual producer prices for some of the starch products for South Africa (e.g. millet and cassava starch), and the need for consistency amongst crops for the comparison. Thus, potential drawback from variations in profit-margin targets by middlemen/retailers and volatilities in product prices must be recognized. On the other hand, the estimated prices could reflect socio-economic impacts of the starch industries that could be useful to policy-makers.

4.5 Results and implications

4.5.1 Primary cassava residues based-biogas and bioethanol production potential

Mobilization of adequate amounts of process residues is imperative for successful commercialization of integrated residue-biofuel production in starch crop industries. The availability of adequate amounts of the residues can be enhanced through scaling up of the agro-processing industries. The household or small-scale starch processing facilities that are wide spread in most developing countries, generate residues that are not technically and economically feasible [21,23,238].

The assessment shows that process residues in the estimated theoretical residues (Fig. 4-5a), accounts for a considerable fraction of the total mass (cassava peels- 49.0%, maize cobs- 26.5%, potato peels- 100%, wheat chaff- 52.7%; sorghum shells- 18.1%). Therefore, integration of the process and field residues is very important in realizing large quantities for commercial-scale bioenergy processes. The technical residue projections (Fig. 4-5a) compared favorably with similar projections for maize (10.08 million t/a versus 10.4 million t/a), wheat (1.4 million t/a versus 2.0 million t/a) and sorghum shells (0.06 million t/a versus 0.2 million t/a) for South Africa [239].

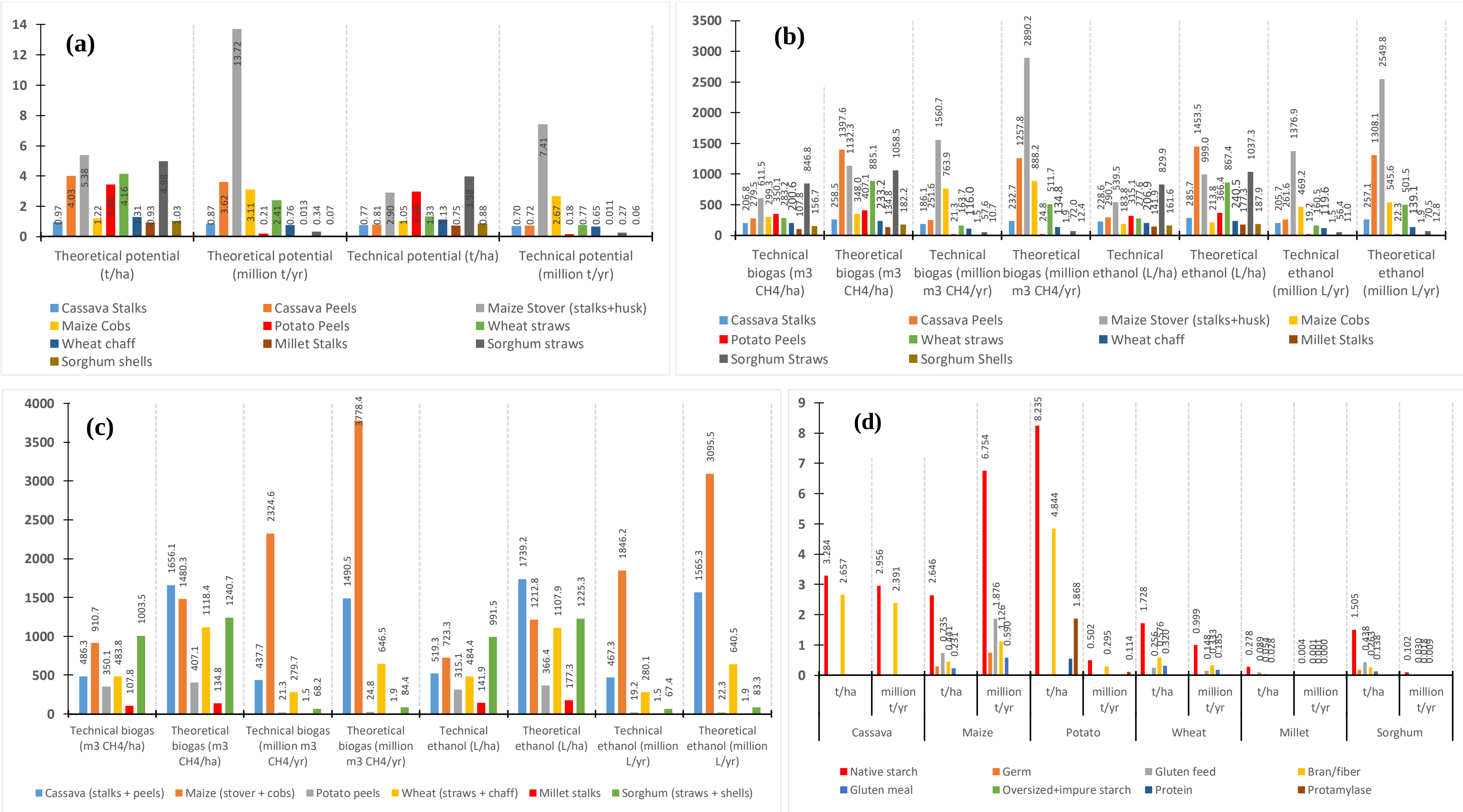

Fig. 4-5: a) Estimated biomass residue generation for major starch crops in South Africa. Estimated potentials for cassava are based on assumption that cassava production and yields for South Africa could reach those in Ghana (third leading producer in Africa); b) and c) present estimates of biogas/bioethanol production potential for the individual and collective primary residues respectively (using the biomass estimates in ‘a’), based on the approach by Kemausuor et al. [190]; d) Estimated capacities of starch and co-products from corresponding crops of the residues in ‘a’.

In addition to the benefits of low cultivation input demands and high starch content, cassava further demonstrates high efficiency in primary biomass residues generation for biofuel production compared to other corresponding starch crops. The estimated technical cellulosic ethanol production potential for maize stover, sorghum stalks and wheat stalks (Fig. 4-5b) were higher than estimates by Mwithiga [191] [539 versus 142, 829 versus 138, 277 versus 143 L/ha, respectively]. In the referred work, a constant but lower recoverability fraction-RF (0.15) and ethanol yields (280 L/t) were assumed for all the studied residues, hence, the similar but lower ethanol production potential obtained (~140 L/ha). On the basis of cultivation area (per hectare), cassava demonstrated the highest primary residue-biofuel potential. The estimated theoretical (maximum) biogas production potential of 1656 m^3 CH_4/ha for cassava (stalks + peels) was 1.12, 1.34, 1.48, 4.07 and 12.3 fold higher than for maize (stover and cobs), sorghum (straw and shells), wheat (straws and chaff), potato (peel), and millet (stalks) respectively (Fig. 4-5c). Similarly, the calculated theoretical (maximum) cellulosic ethanol for cassava (stalks and peel) at 1739 L/ha was 1.42, 1.44, 1.57, 4.75 and 9.82 fold higher than for sorghum (straw and shells), maize (stover and cobs), wheat (straws and chaff), potato (peel), and millet (stalks) respectively (Fig. 4-5c).

In relation to cassava, prospects aimed at commercializing residues-biofuels may focus on developing higher stalk yielding cultivars and strategies for mobilizing large amounts of peel residues, such as industrialization of the starch processes. The technical (minimum) biogas estimates (Fig. 4-5c) showed sorghum had the highest potential of 1003 m^3 CH_4/ha, followed by maize (910 m^3 CH_4/ha), cassava (486 m^3 CH_4/ha), wheat (483 m^3 CH_4/ha), potato (350 m^3 CH_4/ha), and millet (107 m^3 CH_4/ha). Similarly, for the technical cellulosic ethanol production potential (Fig. 4-5c), sorghum at 991 L/ha represented the highest, followed by maize (723 L/ha), cassava (519 L/ha), wheat (484 L/ha), potato (315 L/ha), and millet (141 L/ha). Thus, cassava showed low technical biofuel production potential compared to sorghum and maize.

Cassava peel accounted for approximately 80% of the cassava total theoretical residues (estimated from data Fig. 4-5a). According to Jekayinfa and Scholz [223] the peel, based on Nigeria, has low recoverability (0.2). The relatively low recoverable fraction for cassava peel is attributed to large proportions, 68% of the generated peel, being discarded or used as feed for livestock [86,196]. Consequently, technical biofuel estimates for cassava peel are very low. The situation is the same with cassava stalks that have a RPR of 0.06 (6 % w/w) for the African scenario [223], compared to RPR of 0.51 by Zhu et al. [100] for other places. Therefore, it is very clear that there is need to increase the recovery of cassava residues combined with cultivation of higher stalk yielding cassava cultivars to increase the potential for integration of bioenergy production based on cassava residues.

In the root and tuber starch industries, the projections for residues-bioethanol are comparable to the bioethanol projections from the main crop. Therefore, the main crops (roots and tubers) can be reserved for food uses while exploring biofuel production from the residues, which is a feasible strategy for ensuring food and energy security among the root and tuber growing and processing communities. The estimated theoretical cellulosic ethanol for cassava stalks and peel in this study shows that the corresponding stalks and peel per ton cassava cultivation may generate 108 L of ethanol [estimated using average crop yield of 16.1 t/ha (Table 4.3) and a theoretical ethanol yield of 1739 L/ha (Fig. 4-5c)], which translates to 72% of the root starch's bioethanol estimate (150 L/t for cassava) by Kuiper et al. [84]. Likewise, Virunanon et al. [183] obtained bioethanol yields of 240 L/t for cassava bagasse (fibrous residue from the starch production process).

4.5.2 Commercial starch production capacities

On the basis of cultivation area (Fig. 4-5d), the estimated starch production for cassava (3.28 t/ha) is higher than that for all the cereal/grain crops (maize 1.24, sorghum 2.18, wheat 1.90, and millet 11.8 fold higher respectively). This finding agrees with literature reports that suggest cassava has a higher starch yields than most starch crops (see Table 4.1). However, the obtained starch for potato (8.24 t/ha) was 2.51-fold higher than for cassava. In places like South Africa, potato cultivation is high yielding (average 34.6 t/ha) [240] due to use of genetically improved cultivars and input-intensive cultivation. In contrast, cassava cultivation is based on Ghana's production which is less input intensive with yields (average 16.1 t/ha) that are lower than potato yields [32]. On the other hand, cassava yields have been shown to respond favourably to cultivation inputs including fertilizer, which could be as high as 67 t/ha [241], which exceed that of potatoes. Therefore, under equally improved cultivation measures, the starch per cultivation area obtainable from cassava may be comparable or even exceed that of potatoes.

4.5.3 Electricity and transport fuel capacities

Energy self-sufficiency could be realized in the starch processes through biogas conversion of associated field and process residues. The estimated electricity generation capacities from the residues-biogas (Fig. 4-6a) revealed cassava had the highest theoretical production potential of 5520 kWh/ha, which exceeded the production potential for the corresponding crops by 10.6% , 25.1%, 32.5%, 75.4% 91.9% for maize, sorghum, wheat, potato and millet respectively. Sorghum demonstrated the highest technical potential at 3345 kWh/ha, followed by maize (3036 kWh/ha), cassava (1621 kWh/ha), wheat (1613 kWh/ha), potato (1167 kWh/ha), and millet (359 kWh/ha). Furthermore, the bioenergy projections in Fig. 4-6b, show that theoretically, the biogas generated from the residues could meet all the energy requirements (electrical and thermal) for the corresponding starch processes. In addition, surplus electricity of 4973, 4603, 2401, 397 and 4030 kWh/ha can be generated from cassava, maize, wheat, millet, and sorghum residues respectively (see Appendix A.2). The surplus electricity can be used to support modern food processing and preservation technologies such as, electric refrigeration, freezing and drying, in energy deprived and food insecure agricultural communities.

The biogas production potential from residues of the other established starch crops (excluding cassava residues), could collectively generate approximately 8,984 GWh (technical) or 15,037 GWh (theoretical) electricity per annum (Fig. 4-6a), which could potentially supply 3.8-6.3% of annual national electricity generation for South Africa (approximately 238.5 TWh) [242]. Furthermore, for cassava production capacities of countries like Ghana, electricity generation potential using the biogas from cassava residues could further supply 0.6-2.0% power demand in South Africa (Fig. 4-6a). The substantial biomass residues from starch crops, therefore, provides opportunities for sustainable electricity supply for agro-processing industries in energy deprived areas, which may contribute to mitigating postharvest losses, leading to enhancements in food security and the bioeconomy.

When considering countries such as South Africa, the targeted national biofuel contributions of 2-5% liquid fuel consumptions [243] could be achieved using only the residues of starch crops (2nd generation biofuels), which could eliminate land and food security risks associated with 1st generation biofuel production [244]. From the residues-bioethanol scenarios, petrol equivalence for the considered crops demonstrate similar trends to the bioethanol production potential discussed in section 4.5.1 (shown in Fig. 4-6c), though at 30% lower magnitudes as the estimation was based on energy equivalents. The annual residues-bioethanol capacities for only the established starch crops (minus cassava) could substitute 1.55-2.69 billion L of petrol, while capacities for only cassava (at the assumed cultivation capacities as Ghana) may replace 0.33-1.1 billion L of petrol (Fig. 4-6c). Consumption of petrol in South Africa has been projected at 12 billion L/a [191]. The estimated potential for petrol replacement (i.e. blending prospects) for the established starch crops and the prospective cassava crop, therefore, constitute 12.9-22.4% and 2.8-9.2% of the national petrol consumption respectively. Therefore there is ample potential to meet the national biofuel targets of 2-5% for liquid fuel consumptions [243]. Governmental motivations for the uptake of biofuels in South Africa include socio-economic benefits such as job creation and expansions in rural agricultural investments [243]. To this end, the possible socio-economic impacts of the biofuels versus the current petrol industry must be considered in implementation decisions. Silalertruksa and Gheewala [245] projected that, under equal final energy basis, the labor requirement for cassava and molasses based bioethanol industries in Thailand could be 17-20 fold higher than for gasoline, where direct agriculture jobs accounted for 90% of the projections for the bioethanol. The high labor for the bioethanol were attributed to manual operations and low productivities of the agricultural sector of Thailand [245]. Arndt et al. [246] equally emphasized the reliance of the biofuel job creation potential on the crop choice and farming approach. Therefore, research on the socio-economic impacts of the residue-bioethanol industries is imperative to the selection of beneficial feedstock and industrialization pathways.

4.5.4 Gross revenue potential of residues-bioenergy to the starch industries

Substantial economic contributions from the residues-bioethanol to the starch industry can be envisaged, particularly for the vastly marginalised millet and sorghum. Production of residues-biofuels could therefore serve as an economic driver to the industrial developments of underutilised starch crops. The gross revenue contributions of the residues biogas and bioethanol to the starch industries were estimated based on use as a substitute for LPG and petrol, respectively. Per hectare cultivation area, the estimated gross revenues from sales of biogas ranged from US$14 to US$130 (technical) and US$17 to US$214 (theoretical), where sorghum and cassava showed the highest technical and theoretical potentials respectively (Fig. 4-6d). Total annual gross revenues from biogas sales for the established starch crops and prospective cassava were projected to be US$ 348 million to US$586 million and US$ 56.5 million to US$192 million, respectively (Fig. 4-6d). For the residues-bioethanol scenario, respective gross revenues for the established crops and the cassava were US$1.78 billion to US$3.09 billion and US$0.38 billion to US$1.26 billion (Fig. 4-6d). While the revenue projections for the bioethanol scenarios are greater than the corresponding biogas scenarios, economic advantage of the former is not necessarily implied. Investment costs (capital and production costs) are required for actual profitability assessments and comparisons. Bioethanol could yield maximum gross revenues that corresponds to the following percentages of gross revenues from the starch industries: 14.78%, 30.38%, 2.78%, 18.0%, 43.92%, and 50.92% for cassava, maize, potato, wheat, millet and sorghum respectively (Fig. 4-7). Likewise, for biogas sales, the projected maximum gross revenue contributions to the starch industries were 8.15%, 12.53%, 0.59%, 7.52%, 10.67%,17.24% for cassava, maize, potato, wheat, millet and sorghum respectively (Fig. 4-7).

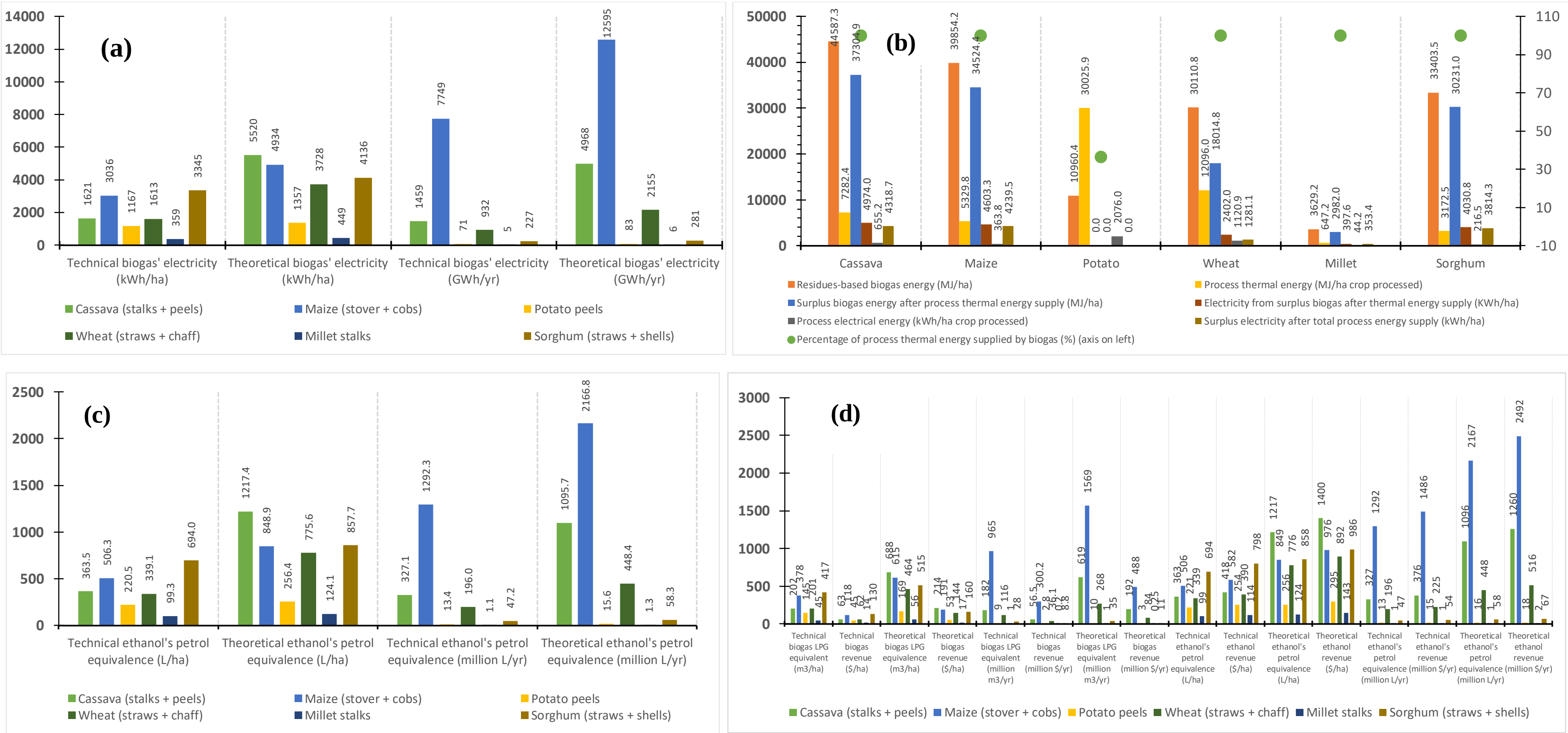

Fig. 4-6: a) Potential electricity generation capacities using the biogas estimates in Fig. 4-5b; b) Estimations of potentials of the residues based biogas to supply energy demands in processing corresponding crops to starch (wet milling); assumed biogas calorific value of 17.5 MJ/m^3 at 65 vol.% CH_4, and biogas to electricity conversion at 1 m^3 (~53% CH_4) to 2kWh [226,247] (see Appendix A.2); c) Petrol equivalents (on an energy basis) for the estimated ethanol production in Fig. 4-5b; d) Estimated gross revenues from sales of biogas and bioethanol.

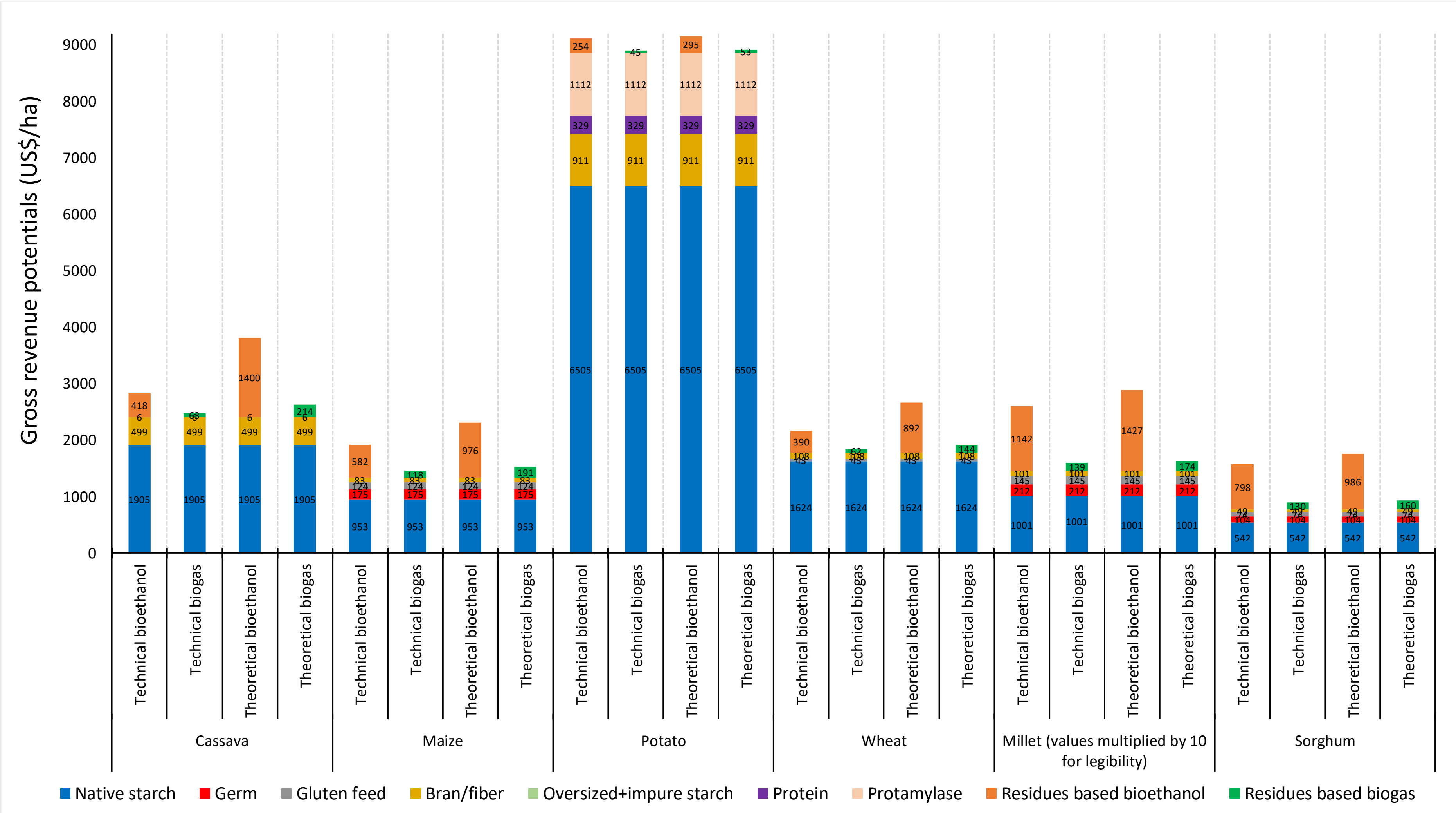

Fig. 4-7: Estimated gross revenue contributions of the residues-biofuels to the respective starch industries. NB: values for millet have been multiplied by a factor of 10 for legibility [NB: Theoretical biofuel = biofuel from total residues generated; Technical biofuel = biofuel from total residues minus fractions for other social uses (e.g. animal feed) (detailed in section 4.4.2)].

4.5.5 Comparative benefits of the residues-bioenergy to industrial developments in the starch industries

The framework for identifying viable starch crops, relative to potential for the design of integrated starch-bioenergy biorefineries and industrial development of the starch industries, was based on a multi-criteria analysis (MCA) (detailed in section 4.1). For the illustrative purposes in the present study, the results discussed in sections 4.5.1-4.5.4 and summarised in Table 4.5, were the considered criteria due to the economic and energy constraints to the starch industries [23,40,43]. The criteria selection (Table 4.5) and weighting in the MCA framework may vary depending on their relevance to the local industrialization concerns, priorities of the decision-maker, and the quality/reliability of the input data used to estimate the criteria. In the present illustration, each criterion is assigned a scale of 1 to 6, where 1 and 6 represent the least and best performing crop respectively (i.e. equal weights for all criteria). The choice of equal weighting is based on the secondary data used in estimating the criteria, thus reliability unknown to inform appropriate weightings.

Table 4.5: Summary of projected potential for the design of integrated starch-bioenergy biorefineries and industrial development of the starch industries [NB: The results are per annum cultivation basis and are projections based on secondary data reports (see section 4.5.5)]

Crop	Theoretical biogas yield m^3 CH_4/ha	Theoretical ethanol yield (L/ha)	Commercial starch yield (t/ha)	Surplus electricity after supplying starch process energies (kWh/ha)	Gross revenue contributions of residues based biogas to starch industry (%)	Gross revenue contributions of residues based bioethanol to starch industry (%)	Total gross revenue (theoretical biogas + starch/coproducts) ($/ha)	Total gross revenue (theoretical bioethanol + starch/coproducts) ($/ha)
Cassava	1656	1739	3.28	4319	8.15	14.78	2624	3810
Maize	1480	1212	2.65	4239	12.53	30.38	1526	2311
Potato	407	366	8.23	0	0.59	2.78	8910	9152
Wheat	1118	1107	1.73	1281	7.52	18.00	1920	2668
Millet	135	177	0.28	353	10.67	43.92	163	289
Sorghum	1241	1225	1.51	3814	17.24	50.92	929	1756

Results of the MCA illustration are presented as a radar plot (Fig. 4-8), which suggests the crop having the largest area as the best performing and vice-versa. Consequently, for this study's illustration conditions, cassava, maize, sorghum, wheat/potato and then millet were predicted to be the highest to least favourable crop with respect to the potential for the development of integrated starch-bioenergy production systems. Cassava demonstrated promises regarding residues-bioenergy potential (Table 4.5). Conversely, sorghum, followed by maize/millet, had the highest economic potential for bioenergy contribution to the starch industry (Fig. 4-8). This could be explained, for sorghum and millet, by the relatively low crop yields (Fig. 4-5d) translating to low starch/co-product revenues, thus, high revenue impacts from the residues-bioenergy. Potato outperformed all corresponding crops with respect to total gross revenue (theoretical bioenergy and starch/co-products sales), although it displayed a low residues-bioenergy potential. Thus, for potato, revenues from the relatively high starch/co-products yield (Fig. 4-5d) were large enough to make up for the comparably low revenues from the bioenergy (Table 4.5). Cassava emerged second to potato regarding total gross revenues (Fig. 4-7), which can also be explained by the relatively low bioenergy contributions to the total revenues for cassava (8-15%) (Table 4.5). For the cereals/grains, the bioenergy benefits to industrial development for sorghum and maize are comparable, while millet showed the least potential (Fig. 4-8).

In general, the considered crops, except for potato, exhibited potential to supply their respective starch process energy needs through residues-biogas conversion, while generating substantial surplus electricity (Fig. 4-6b). The starch industries may achieve energy self-sufficiency through residues-bioenergy conversions. However, relative to the corresponding crops, cassava demonstrates promises because of higher potential for co-production of starch and primary residues-bioenergy (Fig. 4-8). Further enhancement of this advantage for cassava could be achieved by improving the crop yields, achievable through high yielding varieties and advanced cultivation inputs or practices, such as fertilizers and irrigation [32,241].

It must be emphasised that the predicted trend in Fig. 4-8 could vary with the input data. For instance the biofuel yields (ranking) could vary with crop yields (see Appendix A.3). Likewise, the biomass compositions of the residues could vary with the cultivation conditions, crop cultivar and processing approach [248]. Thus, reliability of the input data, relative to the local context of the region under assessment, is essential to the reliability of the MCA framework. Hence, under reliable research context and data sources, the MCA framework could be a useful decision-making tool concerning allocation of scarce land resources for starch crop cultivation and sustainable industry objectives.

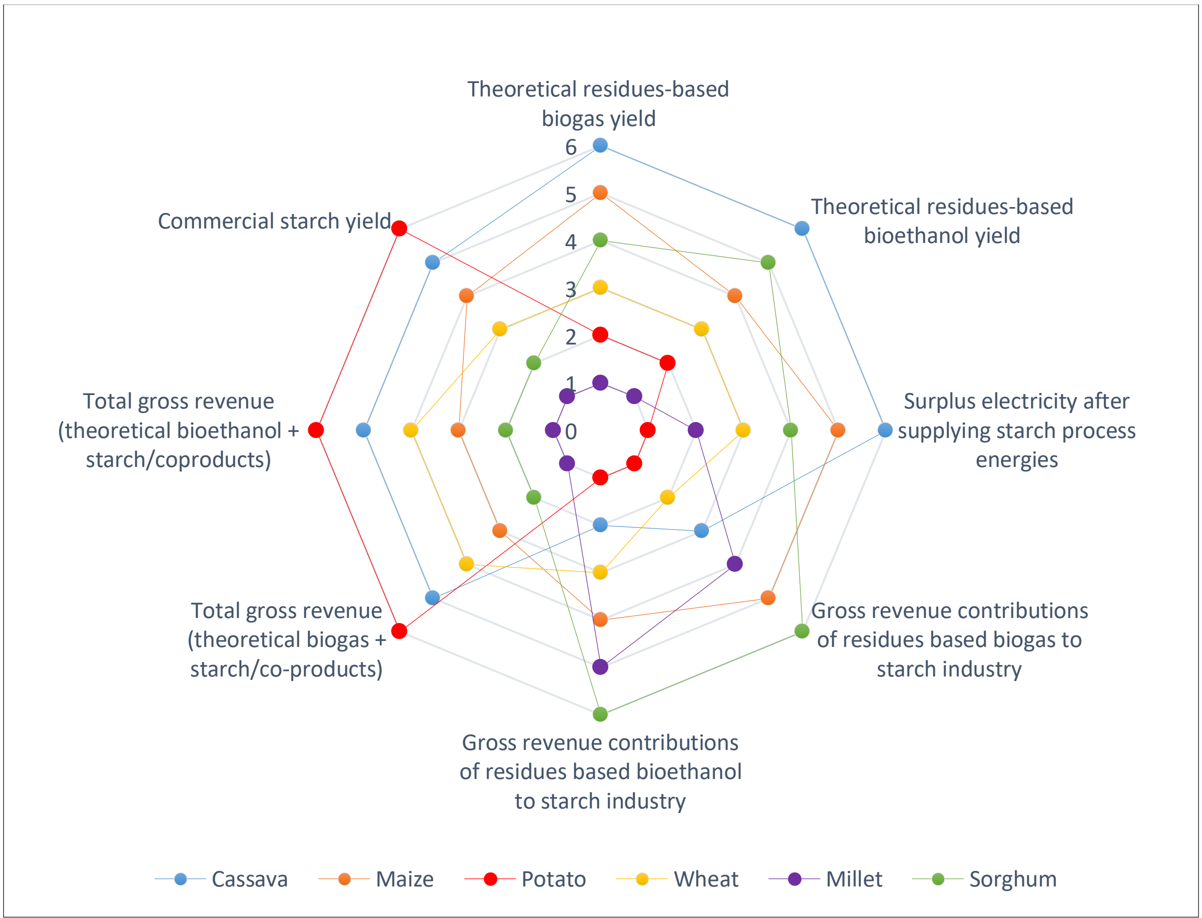

Fig. 4-8: Rankings of the starch crops with respect to potential for the design of integrated starch-bioenergy biorefineries towards advancements of industrialization/bioeconomy (1- least performing & 6- best performing) [NB: illustration result based on per hectare cultivation estimates using secondary data reports (see section 4.5.5)].

4.5.6 General discussions

4.5.6.1 Starch crops food versus bioenergy prospects

Starch crops have been proposed as ideal biofuel feedstock that could address arable land constraints to commercial biofuel production, owing to their high carbohydrate yields and cultivation efficiencies compared to other crops [45,68]. However, food security concerns stand as a major drawback to the proposed use of these biofuel. Based on the results of this study, it is projected that not only will the proposed residues-bioenergy and food crop applications contribute to energy and food security, but will also promote their sustainable development. This projection is deduced from comparable bioenergy potential from the crops versus the residues, as well as similar gross revenue potential from the use of the crops for bioenergy or food production. For instance, the projected bioethanol yield for cassava starch (2415 L/ha) [estimated using 150 L/t cassava, average cassava yield of 16.1 t/ha] is comparable to the bioethanol yields for its corresponding stalk and peel (1739 L/ha) (Fig. 4-5c). Likewise, gross revenue for cassava starch was predicted to be US$1905 per hectare cultivation (Fig. 4-6d), while the conversion of same to ethanol could yield $1908 per hectare [estimated using a bioethanol price of $0.79/L]. Taking into account the economic and food security incentives, and the deficit in starch demands in food industries [16,78], it may be beneficial to reserve the crop starch for food applications while utilising the associated residues on biofuel production.

4.5.6.2 Barriers to implementing commercial residues-based biofuel production

4.5.6.2.1 Profitability constraints

Perceived economic barriers to the conversion of lignocellulosic residues to bioethanol and biogas are the high investment costs associated with the pre-treatment and enzymatic hydrolysis steps in their production [198,215,249]. For instance, cellulase enzymes for enzymatic hydrolysis account for almost 25-50% of total production costs for bioethanol [250,251]. Advances in research to optimise process conditions or schemes, feedstock traits, and adaptive microbes have shown promise in cost reduction [200,252]. For example, a promising cost-effective lignocellulosic ethanol process is the direct use of pre-treated substrates at high solids loading in the SSF process, having beneficial high ethanol yields (≥ 4 % v/v broth) [253]. Related challenges of inhibitors and inadequate enzymes-solids mixing at high solids loading have been addressed through fed-batch feeding of the pre-treated substrates [254]. In essence, the integration of pre-treatment methods to enhance efficiencies of product conversions in the proposed residues-based biogas/bioethanol production systems must be subjected to thorough techno-economic assessments to ascertain profitability impacts.

4.5.6.2.2 Sustainability concerns

Long-term sustainability of bioenergy production requires stability in the derived economic, environmental, and social benefits [55]. Increasing concerns surrounding uncertainties regarding economic, energy efficiencies (input energy versus output), and social benefits of bioenergy as a substitute to fossil energy still prevail [152,153]. Various authors acknowledge the need for integration of sustainability assessments, including land-use, food security, soil erosion potential, energy efficiency, and socio-economic impacts in prospective bioenergy projects [149,153]. The proposed integrated starch and residue-bioenergy (2nd generation) systems could obviate some of these concerns. For instance, conversion of only the technical biomass residues (unexploited fractions from the total generated) to bioenergy eliminates soil fertility impacts associated with removal of all residues from fields and also safeguards demands for alternate social uses, such as livestock feed. Likewise, using the inevitable primary biomass residues for bioenergy generation, while reserving the crop starch as a food commodity eliminates land-use or food security concerns. This brings the economic, environmental, and energy efficiency dimensions to the forefront of the sustainability concerns.

Life Cycle Analysis (LCA) is a well-established technique for evaluating the environmental and energy consequences (risks, impacts, performance) associated with production processes [155]. LCA has been widely used for environmental and energy efficiency evaluations of bioenergy projects, with focused interests on comparative assessments of alternate conversion processes for a product, alternate products from common biomass, or bio-products versus fossil-based alternatives [156,157,159]. For example, LCA has been applied to cassava-based 1st generation bioethanol (using root starch) [152,162] and starch processes [73]. Similar LCA could be used to establish the true sustainability of the proposed integrated starch-bioenergy production systems.

4.6 Future research areas

Future research must be focused on enhancing the reliability of the MCA framework through the incorporation of more dependable input data or criteria. For instance, comparative techno-economic feasibility and sustainability assessments for the integrated starch and residue-bioenergy systems could provide a more reliable profitability statistics, juxtaposed to the total gross revenue used in the present illustration. Furthermore, the need to develop new or expand existing bioenergy policies to reflect current research developments and sustainability concerns, such as consideration of 2nd generation residues-bioenergy, is imperative to their implementation. Equally, the policies must be synchronised with continuous research which calls for broader consultations and collaborations among researchers in academia, related industries and governmental bodies responsible for such policies.

4.7 Conclusions

This study presents estimations of residues-biofuel (biogas/bioethanol) capacities from primary residues of cassava (stalks and peel), maize (stover and cobs), potato (peel), wheat (straws and chaff), millet (stalks), and sorghum (straws and shells). Likewise, projected benefits to the starch industry, evaluated as gross revenue increases and the ability to supply the energy demand for the respective starch processes, have been presented. It was shown that relative to cassava, maize and potato may provide higher potential for residues-biogas production (2324 m^3 versus 1656 m^3 CH_4/ha per annum) and commercial starch (8.24 t/ha versus 3.28 t/ha per annum) respectively. On the other hand, cassava may provide greater residues-bioethanol production potential than maize (1739 versus 1212 L/ha per annum). For all the studied crops (except potato), the estimated residues-biogas production was found adequate for energy requirements (electricity and thermal) in processing the corresponding crops to starch/co-products, plus surplus electricity ranging 397-4973 kWh/ha. Energy self-sufficiency in the starch industries could, therefore, be realised through biogas conversion of associated field and process residues. The surplus electricity can facilitate postharvest operations and provide power for downstream food processing and preservation technologies (e.g. refrigeration, drying), which can increase the shelf-life of both the crops and the residues for food and bioenergy production. Therefore, integrated residues-biorefineries can help in boosting industrialisation of underdeveloped cropping systems such as cassava with multiple socio-economic (job creations in feedstock collection/supply) and environmental benefits to various stakeholders in the value chain. The findings contribute to holistic benefit assessments of integrated starch-bioenergy biorefinery systems that can benefit under developed starch crops.

5 Commercial viability of integrated waste treatment in cassava starch industries for targeted resource recoveries

Chapter summary

The study (Chapter 5) investigated the viability of enhanced wastes resource recovery schemes from conventional treatment of wastes in cassava starch industries (applicable to Specific Objective 2, section 1.3), towards mitigation of the resource (water, energy) and pollution burdens associated with the prevailing waste management systems (anaerobic digestion of the CWW+CB wastes to generate biogas used for starch drying plus disposal of the digestate into watercourses; CS wastes disposal via open burning). The proposed enhanced resource recovery schemes include: (I) CWW+CB conversion to thermal energy + liquid biofertilizer, (II) Integration of CWW+CB and CS conversion to CHP + liquid biofertilizer, (III) Integration of CWW+CB & CS conversion to CHP + solid biofertilizer + usable water. It was shown that, although all the scenarios may be economically viable for commercial operations, only the Case II may ensure energy self-sufficiency in the cassava starch industries. Therefore, the integration of CS into the conventional waste treatment is a promising economic and environmental enhancement strategy for commercial applications in cassava starch industries.

The Chapter 5 was written according to the format of the **Journal of Cleaner Production (Elsevier journal)** and has been published in same:

***Padi RK**, Chimphango A., 2020. Commercial viability of integrated waste treatment in cassava starch industries for targeted resource recoveries. J Clean Prod; 265: 121619 (Published online).*

Declaration by the candidate:

With regard to Chapter 5, pg. 91-117, the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution
Defining the scope of the study, conceptualizing the cassava wastes biorefinery (CWB) schemes, Aspen Plus simulations and economic assessments of the CWBs, analyzing and interpreting results, writing of the manuscript.	87 %

The following co-authors have contributed to Chapter 5, pg. 91-117:

Name	E-mail address	Nature of contribution	Extent of contribution
Chimphango, A.	achimpha@sun.ac.za	Assisted in defining the scope of the study, conceptualization of the CWB schemes, general discussions, and reviewed manuscript.	13 %

Signature of candidate: ………………

Date: ………………………………

Declaration by co-authors:

The undersigned hereby confirm that:

1. The declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 5, pg. 91-117

2. No other authors contributed to Chapter 5, pg. 91-117, besides those specified above, and

3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 5, pg. 91-117, of this dissertation.

Signature	Institution	Date
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Commercial Viability of Integrated Waste Treatment in Cassava Starch Industries for Targeted Resource Recoveries

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Abstract

The commercial viability of an integrated waste treatment process for converting wastewater and bagasse from a 200 t/d cassava starch facility, together with the associated cassava stalks, into bioenergy products and biofertilizer coupled with recovery of water for reuse, was assessed using Aspen Plus® simulations. The wastewater and bagasse are anaerobically digested for producing biogas that is combusted for thermal energy (Case I), or augmented with CS for combined heat and power production via steam boiler and turbo-generator while recovering biofertilizer in liquid or solid form (Cases II and III). In Case I, the biogas produced meets the thermal energy needs for starch drying in the cassava starch facility. Case II demonstrates energy self-sufficiency for the combined heat and power process and generates 28.53 MW as surplus power that is adequate for meeting power demands from the starch facility (~2.17 MW) whereas, Case III generates only 56.5% of the biorefinery's total power demands. In addition, liquid biofertilizer is recovered in Cases I and II while Case III allows for recovery of solid biofertilizer as well as water for reuse in the combined heat and power production, thus reducing the demand for freshwater by 66%. All three cases present potential profitable commercial investment with Net Present Values between US$ 83.4 million and 130 million, depending mainly on wastewater treatment costs and bioelectricity prices, and minimally on biofertilizer and thermal energy prices. Thus, the integration of water recovery and cassava

stalks conversion into cassava waste treatment results in both economic and environmental benefits for the cassava starch industries.

Keywords: Anaerobic digestion; Biofertilizer; Cassava starch wastes resource recovery; Cassava wastewater; Combined heat and power; Integrated cassava waste treatment

5.1 Introduction

Commercial cassava (*Manihot esculenta*) starch extraction involves rasping of the cassava roots, followed by fiber separation, then starch dewatering and product drying. The process consumes large amounts of water (~18 m^3) [44], thermal energy (~445-695 kWh) and electrical energy (~90-260 kWh) [177] per ton of starch produced. Consequently, large volumes of wastewater (CWW), containing ~0.157 kg starch /m^3, are generated at a rate of 12-20 m^3/t of starch produced [44]. Similarly, the separated fiber termed cassava bagasse (CB) is high in starch (~75% w/w) [183]. The high starch contents of the CB combined with the CWW contributes to high organic loadings (8.0-66.2 kg COD/m^3) [51]. Consequently, expensive treatment methods are required for the starch facility to comply with discharge standards [51]. The high resource (water, energy) consumption in starch processes coupled with the high waste treatment costs, necessitates integration of resource recovery with conventional waste treatment [71].

There are many possible conversion routes for the cassava wastes including thermochemical and biological processes. In contrast to thermochemical processes, such as combustion and gasification, anaerobic digestion (AD) is a suitable energy recovery scheme for high moisture agro-industrial wastes [213] such as CWW and CB. The digestate, an effluent of the AD process, contains nutrients such as nitrogen (N), phosphate (P) and potassium (K) thus benefits agriculture as a biofertilizer [178,179]. The digestate can be further treated to recover usable water and a solid biofertilizer [178,179]. Thus, the AD technology is an environmentally benign waste treatment option for CWW and CB with potential for total resource recovery (TRR) of products including energy, biofertilizer and usable water [71,72]. In addition to ensuring cleaner production and supporting the circular bioeconomy scheme [44,255], the subsequent use of the energy, water, and biofertilizer in the cassava starch process or agro-farming activities helps in reducing the high water consumption and pollution associated with cassava starch industries [72].

Despite the potential to benefit more from TRR, AD of CWW and CB is often limited to the recovery of biogas thermal energy in the cassava starch industries, [71,72]. This can be attributed to the fact that the commercial viability of the TRR schemes in cassava starch facilities is not known. Effluent from the AD of CWW containing CB has been used in pastures as irrigation water and fertilizer (fertigation), which improved average cattle head per hectare from 2 to 10 [71]. In cases where starch facilities are located away from the pasture land, the effluent is often discharged into water bodies or neighbouring fields, thus causing serious environmental pollution [71,176]. Thus, the TRR scheme provides an alternative cassava waste treatment process that would benefit starch facilities not annexed to pasture land. For example, Sánchez et al. [71] evaluated the feasibility of supplying energy via a gas engine-based combined heat and power (CHP) scheme to meet energy demands of the cassava starch process, using biogas from the CWW containing the CB. However, the derived biogas was inadequate for the thermal and electricity demands from the facility [71]. Thus, for energy supply that meets total demand, the biogas CHP needed to be augmented with firewood as a feedstock [71].

In cassava growing areas, large amounts of woody stalks (CS), estimated at average CS-to-cassava root ratio of 0.51 [82], are generated and about 10-20% are used as planting materials. Thus, up to 80% CS is left on the cultivation fields as waste [82]. The CS has an average calorific value of 16.3 MJ/kg, making it a potential resource for thermochemical energy applications [175], which when used in CHP production can cover the energy deficits according to Sánchez et al. [71]. The CS, which is generated whenever cassava is harvested for starch production, could be a reliable source of fuel for integrating with the conversion of

CWW and CB for TRR or CHP applications. However, commercial feasibilities of the proposed TRR and CHP schemes must be demonstrated to guide investment decisions.

In this study, feasibility and economics of possible commercial TRR schemes for treatment of CWW and CB generated in cassava starch facilities (CSF) were assessed in three cases for a typical CSF capacity of 200 t cassava starch/d [71,72]. The assessment was done through process simulations in Aspen Plus® (Aspen Technology, Inc., USA), a software program that contains a physical and thermodynamic property database for conventional chemical compounds, and a customized property database for biomass chemicals such as cellulose [256]. In all the three cases, the CWW and CB are treated via anaerobic digestion producing biogas that is combusted for thermal energy (Case I) and augmented with CS for combined heat and power (CHP) production in a steam boiler and turbo-generator while recovering biofertilizer in liquid (Cases II) or solid form (Case III). The energy demands for the CHP in Cases II and III are supplementing by co-combusting the biogas with CS generated by cassava farms supplying cassava to the CSF. The process feasibility assessment involves mass and utility balances based on Aspen Plus® process simulations. The economics are assessed relative to net present values (NPV), internal rate of return (IRR), and minimum expected prices of products/services (MEP). In addition, sensitivity analysis is performed to establish the profitability impacts of changes in major economic variables.

5.2 Methods

The requirements for treating the cassava waste are based on the governing environmental regulations and costs of industrial wastewater treatment in South Africa [257,258]. Under this regulation, industrial effluent discharge into the national sewer systems are controlled by by-laws on acceptable pollutant concentrations and corresponding tariff charges by the local water services authority [257,258]. Accordingly, the treatment of the CWW is deemed mandatory for the cassava starch facility (CSF). Hence, two investment scenarios for the waste conversion facility (WCF) are explored. The first scenario is a partnership agreement (PA) in which a private investor agrees with the CSF to operate the WCF for treating the CWW at the expense of the CSF [185], while selling all generated products to end-users. The PA therefore reflect a private investor incentive of full profit recovery from sales of all products. The second scenario is Business-as-Usual (BAU), which reflects current practices of producing biogas thermal energy by the WCF that is supplied to the CSF at no costs [73]. The BAU is aimed at incentive for the CSF, relative to their prevailing waste management practice of AD of the CB+CWW and obtaining biogas as a by-product (used for starch drying hot air- SDHA). Thus, a scenario where the SDHA is supplied by the WCF at no cost to the CSF may encourage acceptance of such partnership by the latter.

5.2.1 Process capacities for cassava waste treatment

The capacity of the WCF is based on the rate at which the cassava waste is generated from a 200 t starch/d CSF [71,72] that processes approximately 842 t of cassava roots/d [44]. The CSF generates 7.29 t/h CB (dry mass- DM) [44] and 377.83 t/h CWW [176] (Appendix B.1). Assuming that 20% of the generated CS is used as planting material [82], 80% of the CS generated at the farm supplying the cassava roots is processed in Cases II and III for CHP. Furthermore, assuming that the CS mass equals 51% of the mass of the cassava roots supplied to the CSF [82], the CS is supplied for Cases II and III at a rate of 343.54 t/d (14.32 t/h) (Appendix B.1).

5.2.2 Process concepts and simulations

The three TRR cases for cassava waste conversions are conceptualized in Fig. 5-1 & Fig. 5-2. The conversion technologies considered are based on reported feasible technology and laboratory findings in literature.

5.2.2.1 Case I: Conversion of integrated cassava starch wastewater and bagasse to thermal energy and liquid biofertilizer

Case I (Fig. 5-1a) involves conventional activated sludge AD treatment of the CB+CWW to generate biogas (for starch drying hot air- SDHA) and liquid biofertilizer (semi-treated wastewater) [179,259]. Luo et al. [260] demonstrated ~85% COD removal for a cassava ethanol stillage (30-80 kg/m^3 solids; 40-70 kg COD/m^3; COD:N:P ratio of 200:5:1) using an AD system operated at an organic loading rate (OLR) of 11.3 kg COD/m^3.d and hydraulic retention time (HRT) of 5 days. The biogas yield is ~0.22 m^3 CH_4/kg COD removed [260]. The CWW containing CB waste has similar physicochemical properties to the referred stillage, with a projected solids loading of 38.4 kg/m^3 and COD:N:P ratio of 192:4:1 [176]. Hence, the AD performance by Luo et al. [260] is presumed in the present study. It is estimated that ~3257 MJ thermal energy, in the form of hot air (170 ^{o}C), is consumed by the CSF for drying a ton of cassava starch [261]. The derived biogas is thus combusted to generate the SDHA. The AD effluent, with typical NPK contents of 87.5 t N + 12.5 t P + 100 t K per annum for a 200 t/d cassava starch facility, is presumed to be sent to neighboring farms for fertigation applications [71].

In the Aspen simulation (Fig. 5-1a), prior to feeding to the AD reactor, the CB (7.29 t/h) + CWW (377.83 t/h) is preheated to 55 ^{o}C [260] using hot flue gas from biogas combustion. The derived biogas is compressed (1.97 atm) to the combustor, while the effluent (liquid biofertilizer) (377.09 t/h, Aspen prediction) is pumped (3 atm) to a holding tank for onward transfer to end-user farms. The biogas production is projected at 8.175 t/h, with a methane rate of 1.69 t CH_4/h (~2415 Nm^3 CH_4/h), for the considered ~85% COD removal [260] and stoichiometric reactions [57,262,263] (Appendix B, Table B.1). A design specification block (D-spec) is introduced to ensure that the biogas fed to the combustor is just enough to meet heating demands for the AD feed and SDHA, thus, 1.34 t/h biogas is projected as surplus.

Simulation of the combustor is based on a medium pressure (1.97 atm) diffusion gas burner specifications [264], where the biogas and air are compressed (1.97 atm) into a mixing chamber, followed by combustion to generate hot flue gases (1600 ^{o}C & 1 atm, Aspen prediction) [57,264]. The combustion air is supplied at an excess of ~21% stoichiometric requirements (38.96 t/h) to ensure complete combustion and to maintain environmentally allowable flue gas compositions [57]. The hot flue gas is then split for the AD feed heating (33.66 t/h) and SDHA generation (12.14 t/h) (Fig. 5-1a). Sulfur in the flue gas is scrubbed using 20% w/w lime solution (18.77 t/h, Aspen projection), followed by baghouse filtering of particulates prior to discharge into the atmosphere [57] (Fig. 5-1a).

5.2.2.2 Case II: Conversion of integrated cassava starch wastewater, stalks and bagasse to Combined Heat and Power, and liquid biofertilizer

In Case II, the AD liquid biofertilizer is used for similar fertigation application as in Case I (section 5.2.2.1), while the biogas from the AD is augmented with CS to generate CHP (Fig. 5-1b). A steam boiler/turbine CHP system is deemed feasible for the CS-biogas fuel mix [57,180].

In the CHP process, the CS (14.32 t/h) is conveyed to the steam boiler, where it augments biogas (1.69 t CH_4/h) from the AD process as boiler fuel (Fig. 5-1b). The steam boiler and condensing steam turbine were modeled following the protocols of Humbird et al. [57]. The boiler make-up water (33 ^{o}C, 1 atm) (4.12 t/h, Aspen prediction) is controlled by a D-spec to ensure a high pressure (HP) steam condition of 60 atm & 454 ^{o}C [57], resulting in HP steam rate of 132.77 t/h (Aspen prediction). The HP steam is fed to the condensing steam turbine that converts thermal energy to mechanical energy for driving the generator to produce electricity (31.96 MW, Aspen projection). The flue discharge from the steam boiler (203.93 t/h; 400 ^{o}C & 1 atm) is mixed with flue discharge from the AD feed heater (19.97 t/h, 360 ^{o}C) to generate the SDHA (170 ^{o}C & 3 atm) via a flue economizer (Fig. 5-1b).

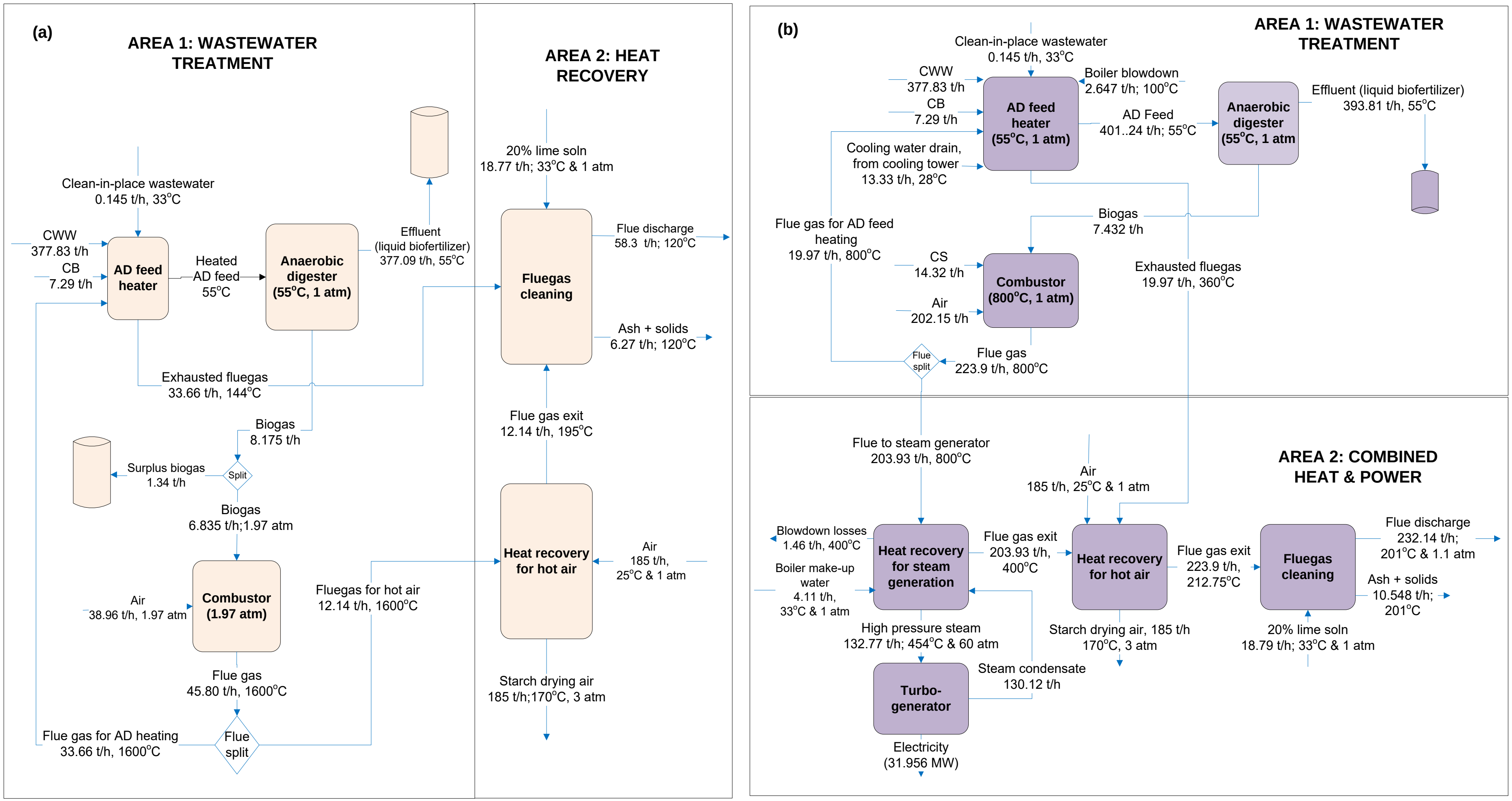

Fig. 5-1: Simplified diagram of the cassava waste conversion scenarios for total recovery of resources (as modelled in this study). (a) Case I- considers conversion of CWW+CB to thermal energy (starch drying hot air) + liquid biofertilizer; (b) Case II- considers conversion of CWW+CB and CS to CHP and liquid biofertilizer. CS = cassava stalks, CWW = cassava starch wastewater, CB = cassava bagasse, CHP = combined heat and power.

5.2.2.3 Case III: Conversion of integrated cassava starch wastewater, stalks and bagasse to Combined Heat and Power, solid biofertilizer and usable water

Case III (Fig. 5-2) is similar to Case II, except that the AD effluent is treated to recover usable water [57]. In the process, the AD effluent (392.38 t/h, Aspen prediction) is pumped (2 atm) to a decanter that separates the sludge (30% solids, 17.1 t/h) [178]. The sludge is first centrifuged to 50% w/w moisture, then dried to 80% DM using a portion of the hot flue gas from the combustor (800 ^{o}C), which is predicted at 32.11 t/h by Aspen Plus. The process generates 5.12 t/h of dried sludge, presumed to have the same N+P+K content as the liquid effluent from the AD, which is designated for solid biofertilizer applications [178,179]. Separated liquid from the decanter and centrifuge (379.58 t/h) is pumped to the aerobic activated-sludge treatment lagoons where 96% w/w of residual organics is converted to CO_2/water (74%) and cell mass (22%) [57]. Residual acids are neutralized with a 50% w/w caustic solution estimated at 3.55 t/h [57] (Fig. 5-2). The effluent is filtered, then clarified using a membrane bioreactor, thereby separating residual organics (1.822 t/h, ~49% w/w moisture). The separated organics contain cell mass desired in the aerobic lagoons, thus, 40% is recycled [57]. Due to dissolved salts, the effluent (382.36 t/h) is further treated by reverse osmosis (RO) to recover 372.85 t/h usable water and 8.08 t/h brine (Aspen predictions) [57]. The recovered water supplies process water for the CHP. The RO-brine, with a typical composition of 6.8 kg N, 0.6 kg P and 11.5 kg K per ton, demonstrates potential as a mineral fertilizer for arable farms or grasslands [178], thus, can be sold as mineral fertilizer.

5.2.2.4 Aspen Plus® process modelling

The Aspen Plus® software facilitates reliable mass and energy balances of processes and has been used in several techno-economic feasibility assessments for bioenergy or biorefinery projects [57,265]. Therefore, the process simulations for the waste conversion options (I-III) were performed in Aspen Plus® v8.8 software based on the feedstock with specified compositions (Table 5.1).

In the simulation, the base thermodynamic model was specified as Electrolyte Non-Random Two liquid (ELECNRTL) and was altered in the CHP to IAPWS-95 which is more appropriate for steam systems [266]. The AD and fuel combustion operations were modelled as stoichiometric reactors using related laboratory results [260] and stoichiometric reactions from literature [57,262]. The AD process, AD effluent treatment to recover water (aerobic activated-sludge and RO treatments), steam boiler/turbine CHP systems, and utility systems (Clean-in-place system, and cooling tower) were modelled according to similar simulations in literature [57].

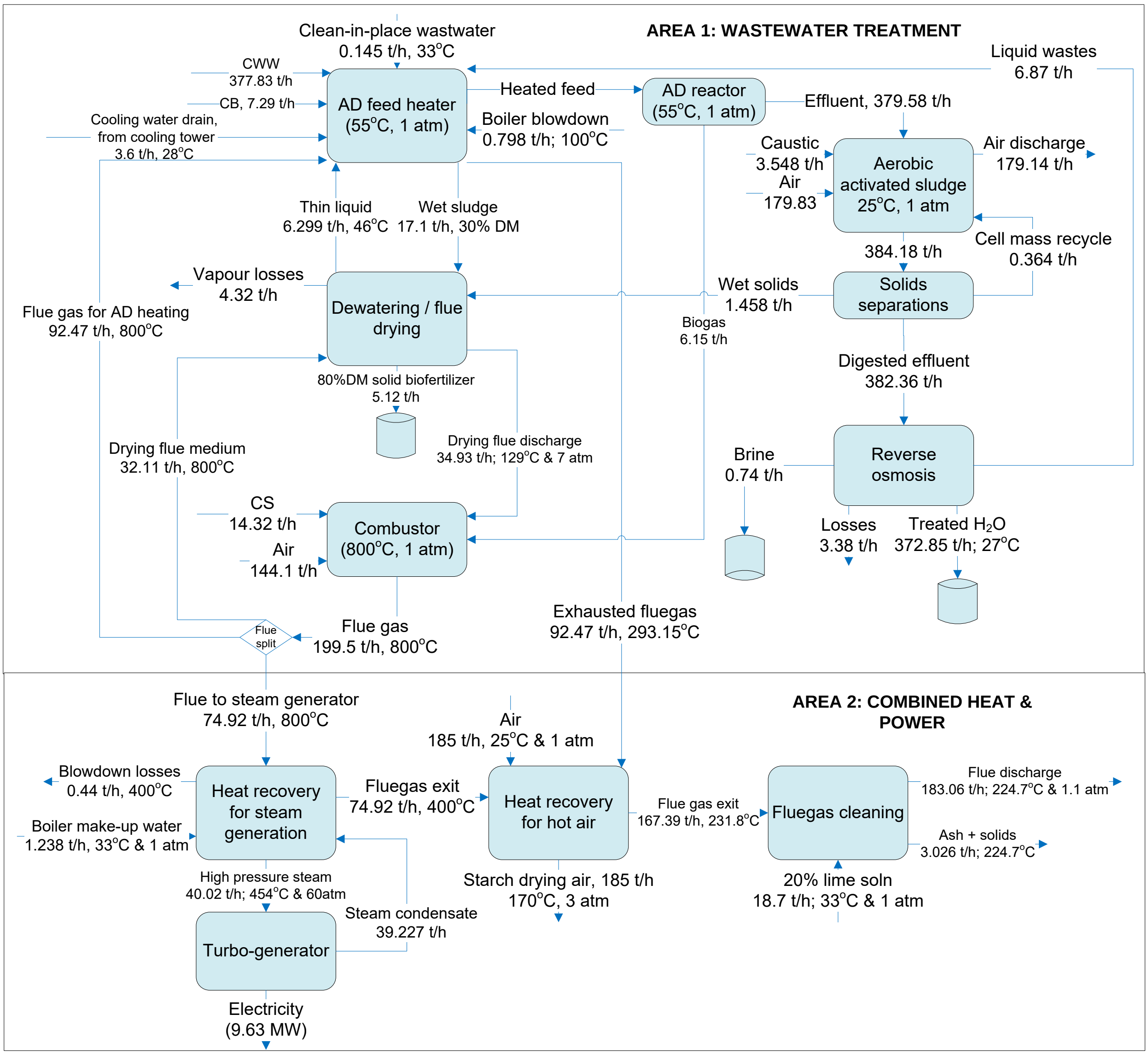

Fig. 5-2: Simplified diagram of the cassava waste conversion Case III (as modelled in this study) that converts CWW+CB and CS to CHP and solid biofertilizer, and recovers water for reuse. CS = cassava stalks, CWW = cassava starch wastewater, CB = cassava bagasse, CHP = combined heat and power.

5.2.3 Profitability assessment

The profitability of the WCFs was assessed relative to economic conditions for South Africa for 2018, based on the illustrative emerging economies for major cassava growing regions [5,267]. The economic assessment for both the PA and BAU investment scenarios, involved projections of total capital investment (TCI), total operating costs (TOC), and revenues. In the TCI projection, mass and energy balances from the Aspen models were used to size and cost the equipment. The purchased costs (PC) for conventional equipment such as pumps were estimated in the Aspen Process Economic Analyzer v8.8, while those for the unconventional equipment such as the RO system were obtained from literature or manufacturers' quotes [57,268]. The PC were updated to the year (2018) and capacity basis of the present study using Eq. 5.1, and was based on various reports [57,269].

$$C_p = C_o \left(\frac{S_p}{S_o}\right)^n \left(\frac{CEPCI_p}{CEPCI_o}\right) \qquad (5.1)$$

Where: C- purchased equipment cost; S- equipment capacity; n- capacity scaling exponent; CEPCI- chemical engineering plant cost index; p- value for the present study; o- reference value.

Furthermore, the updated PC were used to estimate the installed costs via available published reports on installation factors [57,269]. The TCI was then estimated using the total installed costs as shown in Table B.2 (Appendix B). The TOC was estimated as sum of the total variable costs (TVC), total fixed costs (TFC) and plant overhead cost (POC) (Appendix B, Table B.2).

Revenues from product sales were estimated based on prevailing market prices or substituting end-uses (Table 5.2). For instance, the solid as well as the liquid biofertilizer prices were estimated based on potential N-P-K fertilizer replacements, reported to be 87.5 t N + 12.5 t P + 100 t K per annum [71] (Table 5.2). In addition, the WCF charges the CSF for treating the CWW, an amount based on treatment cost reports for organic wastewater [257,258] and the extent of CWW treatment, thus, semi-treatment (Case I-II) or total treatment (Case III) (Table 5.2). In Case I, surplus biogas is presumed to be sold to neighboring households as a cooking fuel (Table 5.2).

In assessing the profitability, the estimated TCI, TOC, and revenues, together with the assumed economic parameters and operating conditions (Table 5.2), were used to develop a discounted cash flow analysis, which was applied to predict the Net Present Value (NPV) (Eq.

5.2). The NPV was subsequently used to estimate the Internal Rate of Return (IRR), which is the discount rate at which the NPV equals zero. Minimum Expected Prices of product/service-MEP (bioelectricity, SDHA, biofertilizer, RO-brine, CWW treatment charges) was estimated as the price that ensures the expected IRR of 9.7% [266,270] at fixed market prices for the co-products (Table 5.2).

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+d)^t} - C_0 \qquad (5.2)$$

Where: NPV- net present values; C_t- net cash flow at time t; C_0- initial investment; t- time of cash flow; T- plant lifetime; d- discount rate

Potential investment risks were evaluated through sensitivity analysis, involving estimations of IRRs for a 50% increase or decrease [185] in major economic variables- total operating costs (TOC), product/service prices, feedstock price, and fixed capital investments (FCI).

Table 5.1: Chemical composition of the cassava starch wastes used as feedstock in the Aspen Plus simulations

Cassava bagasse (CB); % (w/w), dry basis [a]		**Cassava stalks (CS); % (w/w), dry basis [b]**		**Cassava starch wastewater (CWW); kg/m^3 CWW**	
Starch	75.10	Cellulose	31.4	Lignin [c]	0.03
Cellulose	4.11	Starch	35.7	Carbohydrates (starch) [c]	0.375
Hemicellulose	4.20	Xylan	8.2	Lactic acid [c]	1.54
Lignin	1.20	Mannan	2.3	Acetic acid [c]	0.38
Total ash	11.90	Arabinan	1.3	Oil + grease [d]	0.3
Crude fats	1.64	Galactan	1.4	Protein [d]	2.3
Crude protein	1.85	Lignin	14.9	Total nitrogen [c]	0.112
-	-	Protein	1.1	Total phosphorous [c]	0.028
-	-	Total ash	3.8	Cyanide [c]	0.0035
-	-	-	-	Water	994.24

[a] Reports by Virunanon et al. [183], except crude fats and crude protein that are based on average reports [51]; [b] Reports by Martin et al. [109], where mannan, arabinan and galactan are averages; [c] Based on Colin et al. [176]; [d] Reports by Zhang et al. [51].

Table 5.2: Assumptions in estimating the prices of products/services, and the considered profitability/operating conditions for the cassava waste conversion processes

Economic factors	Estimates/2018 values (US$ per kg, or per kWh for electricity)	Reference(s)
Sellable bioelectricity (surplus) [a]	0.1282	[266,270]
Starch drying hot air [b]	0.0005	
Cassava starch wastewater (CWW) treatment charges [c]	0.0068 (Semi-treatment, Case I-II); 0.0136 (Total treatment, Case III)	[257,258]
Solid biofertilizer [d]	0.00142	[71,271]
Liquid biofertilizer [e]	0.000018	[71,271]
Brine waste from reverse osmosis unit (mineral fertilizer) [f]	0.00226	[178,271]
Surplus biogas (applicable to Case I only) [g]	0.0328	
Project lifetime	30 years	[57,259]
Operating hours	8410 h/a	[57]
Financing scheme	40% equity & 60% loan	[57,265]
Loan terms	8% interest & 10 years recovery	[57]
Discount & inflation rates	9.7% (real term) & 5.7% respectively	[266,270]
Construction period	1 year	[270]
Start-up time	6-months	[265]

[a] Calculated as 20% in excess of coal power price of 0.1068 US$/kWh (www.eskom.co.za) [272], supported by South Africa's agenda towards green electricity [270]; [b] Estimated as costs of equivalent coal on energy basis [(27142 MJ/hr x 0.08$/kg coal)/23.25 MJ/kg coal]; $93.40/h], plus flue economiser's depreciation ($0.45/h), plus associated labour cost ($0.35/h); [c] Cases I-II and Case III's CWW treatment credit were estimated as 40% and 80% (respectively) of avg. wastewater treatment costs (0.001-0.033$/L) for South Africa, [257,258], while assuming the 20 - 60% offsets costs of pumping the CB+CWW to the waste conversion plant, and pumping the liquid biofertilizer (Cases I-II) to the farms; [d] Based on NPK content of 87.5 t N + 12.5 t P + 100 t K per annum [71] and 2018 fertilizer prices- Liquid nitrogen ($230/t), diammonium phosphate- DAP ($480/t), potash ($350/t) [271]; [e] Estimated similar to item 'd' while assuming negligible value of the water component; [f] Presumes NPK content of 6.8 kg/t N+0.6 kg/t P+11.5 kg/t K [178] and 2018 fertilizer prices (item 'd'); [g] Based on energy equivalence of LPG (1 kg biogas = 0.2 kg LPG) and average LPG price of $0.164/kg for South Africa [234].

5.3 Results and discussions

5.3.1 Mass and energy balances predicted by the Aspen Plus® simulations

Predictions in Aspen Plus® show that the biogas from AD of the CWW+CB (Case I) is enough for meeting the thermal energy demands of the CSF, and a surplus of 1.34 t/h biogas is projected (Table 5.3). However, according to the predictions, close to 3.6% of the TOC (Fig. 5-3b) was through the consumption of 360 kW of power (Table 5.3), which is presumed to be supplied from the grid at a price of $0.1068/kWh [273]. Therefore, thermal energy generation from biogas derived from CWW and CB constitutes thermal energy self-sufficiency for the cassava starch processes, similar to previous studies [72,73].

In Case II, the Aspen simulations show that ~31.96 MW of electricity (Table 5.3) can be generated in addition to the thermal energy and liquid biofertilizer. Therefore, the integration of the CS (14.32 t/h) in cassava waste conversion provides additional energy to meet the total energy demands of the WCF and CSF. Power demands for the WCF were predicted at 3.43 MW, which is the gross power minus net power (Table 5.3), representing ~11% of the total power generated. The surplus net power of 28.53 MW (Table 5.3) can supply power to the host CSF (~2.17 MW) [177]. The excess power, i.e. the net power minus starch process power (26.36 MW), can provide green electrification for similar agro-processes in energy deprived regions, thus contributing to the bioeconomy.

Treatment of the AD effluent to recover solid biofertilizer (80% DM) and the use of this treated water for CHP production in the WCF (Case III) results in reduced power supply for the WCF. However, the recovery of the solid biofertilizer allows the water to be reused, thereby mitigating ~66% of the freshwater demands for the WCF. The gross power projection of 9.63 MW (Table 5.3) can supply only 56.5% of the total power demands by the WCF Case III [WCF power demand = consumed gross power (9.63 MW) + make-up power import (7.41 MW), Table 5.3]. Therefore, nearly 7.4 MW make-up electricity is presumed to be imported from the grid for the Case III (Table 5.3). The substantial power import accounts for ~24% of the TOC (Fig. 5-3b), hence, imperative to the economics. Likewise, reuse of the recovered water (373 t/h, Table 5.3) reduces the amount of freshwater required, thus only 192 t/h freshwater (Process make-up water, Table 5.3) were needed to meet the process water demands for Case III. Hence, regardless of the inadequate energy supply, Case III can offer opportunities for mitigating freshwater and pollution burdens of CSFs, relative to the direct disposal of CWW+CB wastes into water bodies or surroundings [71].

Table 5.3: Summary of the projected feedstock capacities and Aspen Plus® predicted mass and energy balances for the simulated cassava starch waste conversion processes

Process simulation outcomes		Units	Case I	Case II	Case III
Mass results	CWW [a]	t/h	377.83	377.83	377.83
	CB (dry mass) [a]	t/h	7.29	7.29	7.29
	CS (25% moisture) [a]	t/h	-	14.32	14.32
	Liquid biofertilizer [b]	t/h	377.09	393.81	-
	Solid biofertilizer [c]	t/h	-	-	5.12
	Process make-up water (import) [d]	t/h	15.02	2529.53	192.10
	Recovered treated water [e]	t/h	-	-	372.85
	Surplus biogas [f]	t/h	1.34	-	-
	RO brine (mineral fertilizer) [g]	t/h	-	-	0.74
Energy results	Flue gas for solid biofertilizer drying (800 °C) [h]	t/h	-	-	32.11
	Export hot air for starch drying (170 °C) [i]	t/h	185	185	185
	High pressure steam for power generation (60 atm, 454°C) [j]	t/h	-	132.77	40.02
	Gross electricity generated [j]	MW	-	31.96	9.63
	Net electricity (surplus after in-house supply, for export) [k]	MW	-	28.53	-
	Make-up process electricity (import) [l]	MW	0.36	-	7.41

[a] Total wastes projection for the considered 200 t starch/day facility (Appendix B.1); [b] Aspen prediction for anaerobic digestion (AD) effluents for Cases I-II (Fig. 5-1); [c] Dried solids (20% moisture) obtained from AD sludge in Case III (Fig. 5-2); [d] Total process water was predicted similar to Humbird et al. [57], comprised boiler make-up water (Case I- 0 t/h; Case II- 4.106 t/h; Case III- 1.238 t/h), clean-in-place water (Case I- 15.02 t/h; Case II- 15.028 t/h; Case III- 15.028 t/h), and cooling tower make-up water (Case I- 0 t/h; Case II- 2510.25 t/h; Case III- 548.52 t/h). Process make-up water is, thus, calculated as total process water minus treated wastewater recovered (see item 'e'); [e] Aspen prediction for treated wastewater recovered from the reverse osmosis unit (Fig. 5-2); [f] Predicted surplus biogas after supplying demands for AD feed heating and hot air generation in Case I (Fig. 5-1); [g] Aspen Plus projected brine solution from the reverse osmosis system in Case III (Fig. 5-2); [h] Projected (Aspen) flue gas required to dry the centrifuged sludge (50% solids) from the AD reactor to 20% moisture (section 5.2.2.3); [i] Hot air (170 °C) projected for drying starch in the host 200 t starch/d facility, based on ~3257 MJ thermal energy required for drying a ton of starch [261]; [j] Projected (Aspen) high pressure steam from the boiler to the turbo-generator and resultant total power generated; [k] Estimated as gross power generated minus total process power demands in the waste conversion facility (mainly for pumps, conveyors, compressors); [l] Total or additional electricity imported from the grid to augment electricity generated in-house (if any). Estimated (for Case II-III) as gross power generated minus total electricity demands. Case I [CWW+CB conversion to thermal energy + liquid biofertilizer]; Case II [CWW+CB+CS conversion to CHP + liquid biofertilizer]; Case III [CWW+CB+CS conversion to CHP + solid biofertilizer + usable water]. CHP = combined heat and power, CS = cassava stalks, CWW = cassava starch wastewater, CB = cassava bagasse

The use of available CS (14.32 t/h, Table 5.3), equivalent to 80% of the CS generated by the host CSF's cassava feedstock farms, to supplement energy sources in the integrated CSF and Case III still results in process energy deficits. The total in-house energy supply will demand an additional 12.32 t/h CS (Aspen prediction), corresponding to 86% of the present supply. Strategic measures for supplying the additional CS may include sourcing from external farms where the cassava is intended for uses other than starch production, such as local food consumptions. Furthermore, in the present study, an average CS-to-cassava ratio of 0.51 was assumed [82]. Considering the wide ranging CS-to-cassava yield reports (0.19 - 0.85) [82], measures of cultivating high CS yielding varieties could ensure ample CS supplies by same farms delivering cassava to the CSFs, thus, a potential means to energy self-sufficiency in cassava industries.

5.3.2 Total capital investments and operating costs estimates based on the Aspen Plus® simulations

Projected TCIs for the WCFs range between US$51.88 million – US$152.23 million, where Case I and Case II exhibited the least and highest, respectively (Fig. 5-3a). Compared to Case III, the high TCI for Case II can be attributed to combined cost impacts of the high CHP (31.96 MW vs 9.63 MW, Table 5.3) and wastewater treatment (WWT). Installed costs of the WWT and CHP contribute the most to the TCIs (Fig. 5-3a). Relative to the TCI, WWT accounts for 52.40% (I), 18.29% (II) and 33.25% (III) (Fig. 5-3a). Likewise, the CHP contributes 30.56% (II) and 16.45% (III) (Fig. 5-3a). Specific CHP installed costs (installed cost per electricity capacity), were predicted at US$1460/kW (II) and US$2363/kW (III) (Fig. 5-3a), thus, comparable to reported values for adjusted capacities for biomass CHPs ($500-2000/kW) [274].

The TOCs were predicted at US$ 8.87 million/a (I), US$28.5 million/a (II) and US$28 million/a (III) (Fig. 5-3b). In relation to the TOC, the projected CS price ($0.051/kg, Appendix B- Table B.2) and income tax (28% of net income, Appendix B- Table B.2) contributes the highest with 21.52% (II) or 21.89% (III) (CS price), and 43.69% (I), 26.47% (II) or 21.72% (III) (income tax) (Fig. 5-3b).

The TCI and TOC can, therefore, be minimised through influential government policies, such as the exemptions of bioenergy or waste treatment facilities from income taxes or equipment import duties [258,274]. Furthermore, costs of transportation could potentially impact the CS price [274]. Hence, cultivation of high CS yielding varieties of cassava could help reduce the CS prices [82], leading to reductions in the TOC.

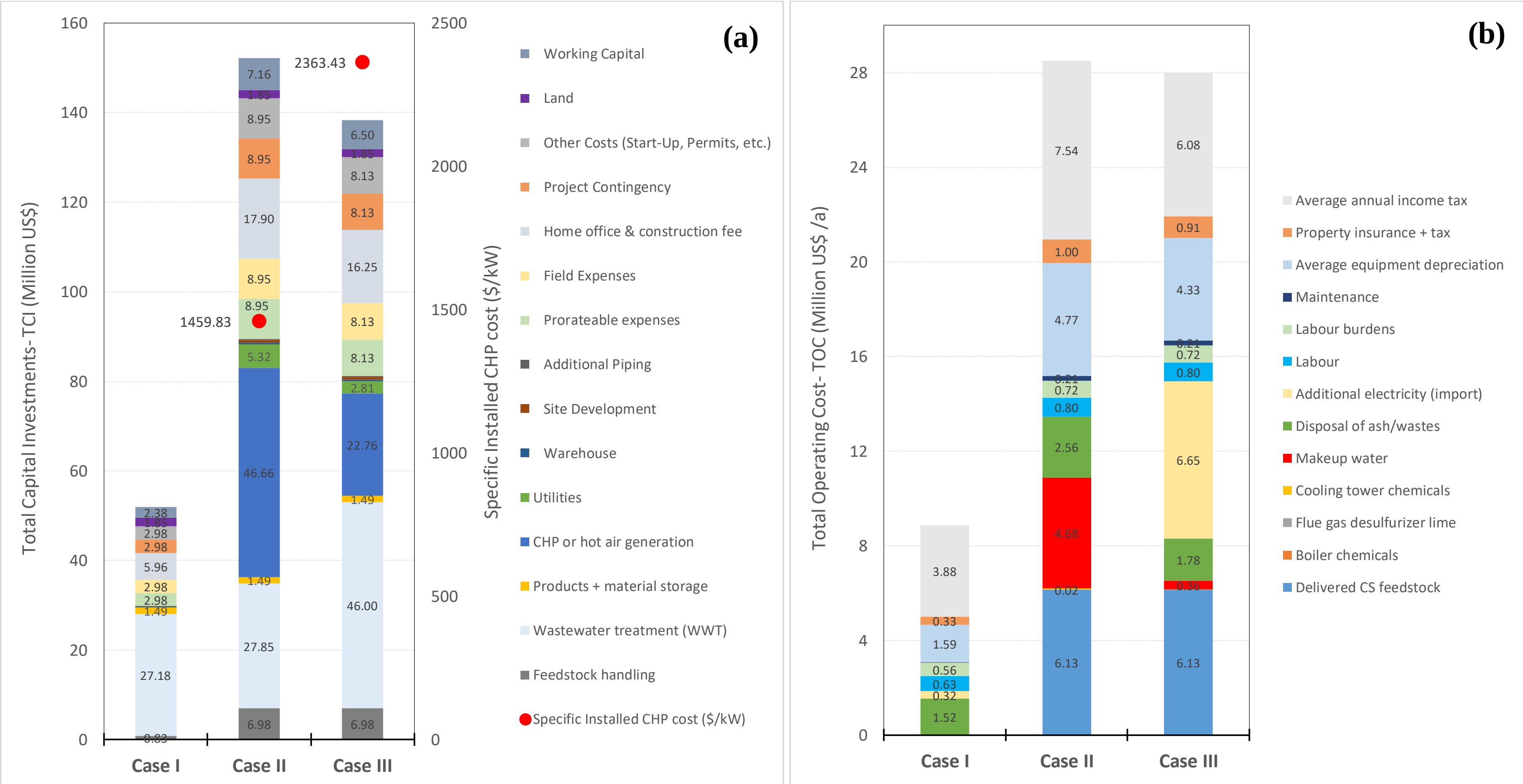

Fig. 5-3: (a) Total capital investments (TCI) for the cassava waste conversion processes (see details in Appendix B, Table B.2); (b) Total operating costs (TOC) of the cassava waste conversion processes. Case I [CWW+CB conversion to thermal energy + liquid biofertilizer] (see details in Appendix B, Table B.2); Case II [CWW+CB+CS conversion to CHP + liquid biofertilizer]; Case III [CWW+CB+CS conversion to CHP + solid biofertilizer + usable water]. CHP = combined heat and power, CS = cassava stalks, CWW = cassava starch wastewater, CB = cassava bagasse.

5.3.3 Profitability analysis for the cassava waste conversion processes based on the Aspen Plus® simulations

Integration of the proposed TRR schemes into conventional waste treatments in the CSFs are economically viable for commercial operations. Both the PA investment where the starch drying hot air is sold to the CSF ($0.0005/kg, Table 5.2), and the BAU investment where the thermal energy is supplied at no costs, demonstrated profitability for all cases (I-III), with NPVs ranging US$ 83.4 million-130 million or IRRs ranging 20.07-38.89% (Fig. 5-4a). Minimal profitability impacts by the revenues from the thermal energy sales can be inferred (Fig. 5-4a). This assertion is further supported by the economic sensitivity analysis results, where 50% increase or 50% decrease in the thermal energy price resulted in similar IRRs (Fig. 5-5). Case II demonstrated a better profitability than Case III (Fig. 5-4a), which can be attributed to the substantial surplus electricity generation (28.53 MW, Table 5.3), accounting for ~58.7% of total revenues (Appendix B, Table B.3).

High costs of transportation or related infrastructure for the biofertilizer and RO-brine applications in agriculture, perceived as potential barriers to implementation [178], can be mitigated through supplying the biofertilizer or RO-brine at zero value by the WCF. The negative MEPs prediction for the co-product biofertilizer (I-III), RO-brine (III), biogas (I), and SDHA (I-III) (Fig. 5-4b) suggest their sales have little impacts on the economics of the WCF. In essence, the referred co-products can be supplied to end-users at no costs, except for transportation charges. The considered CWW treatment costs ($0.0068-0.0136/kg) and bioelectricity sales ($0.128/kWh) (Table 5.2) were the major contributing factors to the economics (Fig. 5-4b).

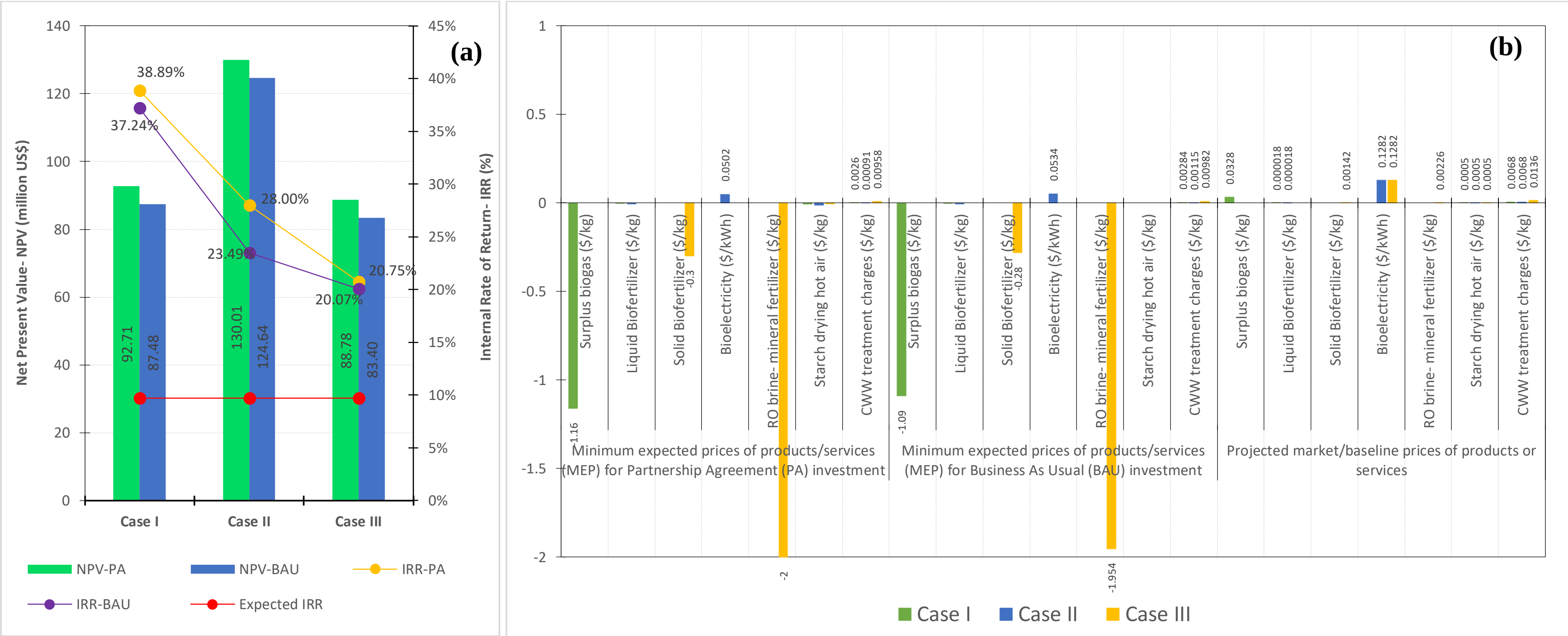

Fig. 5-4: (a) Profitability results for the studied cassava waste conversion processes (CWCP) showing the projected Net Present Values (NPV) and Internal Rate of Return (IRR); (b) Minimum expected prices of products/services (MEP) vs the projected market/baseline prices for the studied CWCP. Case I [CWW+CB conversion to thermal energy + liquid biofertilizer]; Case II [CWW+CB+CS conversion to CHP + liquid biofertilizer]; Case III [CWW+CB+CS conversion to CHP + solid biofertilizer + usable water]. CHP = combined heat and power, CS = cassava stalks, CWW = cassava starch wastewater, CB = cassava bagasse; PA = Partnership Agreement investment (where starch drying hot air is sold to the host cassava starch facility-CSF), BAU = Business as Usual investment (where starch drying hot air is supplied to the CSF at zero costs).

The Case II waste conversion, where CHP + liquid biofertilizer are recovered, presents a strategic means to operating cost reductions in the CSF. In Case II, the predicted MEP for the surplus bioelectricity ($0.0502-0.0534/kWh, Fig. 5-4b) is ~50% less than the grid power price ($0.1068/kWh) [273], thus possibilities of low cost power supply to the host CSF. In addition, the MEP for CWW treatment charges for the prevailing waste treatment approach (Case I) is ~2.47-2.86 folds higher than the prediction for Case II (Fig. 5-4b). The potential decrease in CWW treatment cost or electricity prices, in Case II presents opportunities for operating cost reductions in the cassava starch processes. Hence, Case II scheme can offer solutions to sustainable energy supplies and cost reductions for expansion of cassava starch industries, particularly in energy deprived cassava growing areas, such as Thailand and Nigeria, where energy contributes a considerable share of the production cost (14-25%) [12,44].

5.3.4 Economic sensitivity analysis

Changes in the CWW treatment charges, FCI, TOC, CS feedstock price, and bioelectricity price could present risks to the investment in the WCF. The corresponding IRRs for the +50% and -50% changes in prices for the co-product biofertilizer (I-III), RO-brine (III), biogas (I), and SDHA (I-III) were similar (Fig. 5-5), thus, fluctuations in their prices pose nominal risks to the investment in the WCF (Cases I-III). This finding is in agreement with similar reports for a farm waste based AD CHP system [178]. In contrast, the ±50% changes in the CWW treatment charges (I-III), FCI (I-III), TOC (I-III), bioelectricity price (II), and CS feedstock price (II-III) had notable impacts on the IRRs (Fig. 5-5), thus, presenting possible means to investment risks. Relative to the risks on the investments, the decreasing order of importance of the referred variables is: Case I- CWW treatment charges > FCI >TOC (Fig. 5-5); Case II- FCI > Bioelectricity price > CWW treatment charges >TOC > CS feedstock price (Fig. 5-5) and Case III- CWW treatment charge > FCI > TOC > CS feedstock price (Fig. 5-5).

Hence, the suggested strategies for reducing the TCI, TOC, and CS price in section 5.3.2 could help mitigate the risks to investment in WCF.

Susceptibility of the economic viability of the WCF to the CWW treatment charges is more pronounced in Case III. With the exception of the 50% reduction in CWW treatment charges for Case III, ±50% changes in the considered variables (TOC, FCI, product prices) still result in profitability (IRR > 9.7) for all the cases (I-III) (Fig. 5-5). The unprofitable outcome in Case III can be attributed to the high CWW treatment charges considered ($0.0136/kg), due to the proposed complete treatment of CWW to recover usable water, compared to Cases I and II ($0.0068/kg) where the CWW is semi-treated for use as liquid biofertilizer (Table 5.2).

The economic implications of semi-treating the CWW for liquid biofertilizer uses (I-II) depends on environmental regulations for use of AD digestate as biofertilizer. Additional costs for treating the liquid biofertilizer to comply with environmental standards are anticipated [275]. The AD digestate may contain disease-causing microorganisms or materials, which may necessitate further treatment for compliance with environmental standards [178]. Drying of the solid biofertilizer in Case III, using a portion of the hot flue gas (800^{o}C) (Table 5.3), sanitizes the biofertilizer for direct applications on farmlands [179]. The anticipated digestate treatment costs, therefore, mainly apply to the liquid biofertilizer in Cases I and II.

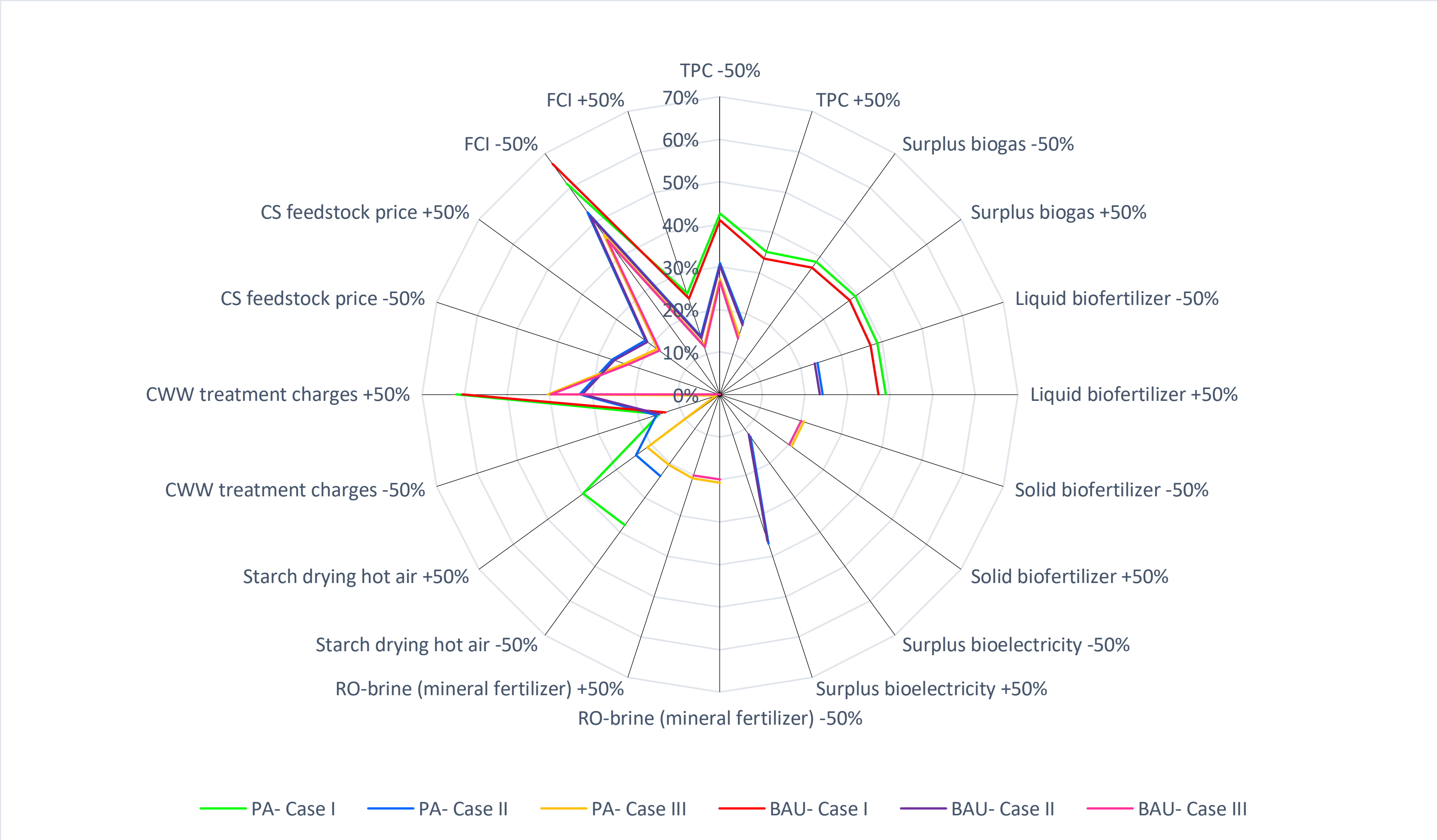

Fig. 5-5: Sensitivity analysis results showing the Internal Rate of Returns (IRR) for ±50% changes in selected variables for the studied cassava waste conversion processes. Case I [CWW+CB conversion to thermal energy + liquid biofertilizer]; Case II [CWW+CB+CS conversion to CHP + liquid biofertilizer]; Case III [CWW+CB+CS conversion to CHP + solid biofertilizer + usable water]. CHP = combined heat and power, CS = cassava stalks, CWW = cassava starch wastewater, CB = cassava bagasse, FCI = Fixed capital investment, TOC = Total operating cost, PA = Partnership Agreement investment (where starch drying hot air is sold to the host cassava starch facility-CSF), BAU = Business as Usual investment (where starch drying hot air is supplied to the CSF at zero costs).

5.3.5 Implications of the wastes conversions for cleaner production and sustainability in the cassava starch industries

The results from the WCF simulations (sections 5.3.1-5.3.4) provide insight into the viability of waste material recoveries from cassava cultivation (CS) and processing (CB+CWW) for co-conversion to bioenergy, biofertilizer, and treated water for self-use in cassava starch industries. The WCFs can, therefore, facilitate inter-organizational partnerships between the cultivation and processing sectors towards a mutually beneficial cleaner production system that could contribute to sustainable reductions in resource and environmental burdens in the cassava industries. The WCF Case III, with potential to reduce freshwater consumption (~66%) (section 5.3.1), safeguards scarce water resources, hence, it is a feasible water management technique in the starch industries. Furthermore, replacing non-renewable fossil energies in the CSFs [73] with renewable bioenergy from the wastes, and augmenting the chemical fertilizers in cassava cultivation [72] with the green biofertilizer enhances the circular bioeconomy and cleaner production, thus, presenting avenues to promote sustainability in the cassava starch industries [255,276]. Hansupalak et al. [72] demonstrated potential for reducing carbon footprints (CF) in cassava starch industries via in-house CB+CWW biogas energy supply, where cassava cultivation contributed 60% of the CF. Further improvement in the environmental savings, through the proposed WCF strategies of co-converting wastes from the cultivation (CS) and the starch processes (CB+CWW), can, therefore, be envisaged. For instance, environmental impacts associated with CS disposal by burning [82] can be mitigated through such WCF schemes. Concerning the derived socio-economic benefits of the WCF, towards its sustainability [255,277], the prospects to create jobs for CS collectors/suppliers and WCF workforce, as well as the potentials to generate additional income for farmers (CS sales) and CSFs (surplus power sales) are imperative.

5.4 Limitations of the study and future research

Literature gaps on in-depth chemical and bacteriological compositions of the CWW+CB-based liquid or solid digestate (biofertilizer) posed limitations to the process and economic concepts for the WCF. Establishing the compositions will facilitate reliable process designs for digestate treatment, to comply with environmental standards for biofertilizer uses [275]. For instance, chlorination may be required to sanitize the digestate [179]. Reliable process designs and digestate compositions will enable realistic costing for the digestate and CWW treatment and biofertilizer benefits. The predicted MEPs for CWW treatment charges in the proposed WCFs (US$ 0.0009-0.00284/kg) may impact the operating costs, and in essence, the profitability of the CSF, hence, should be investigated for implementation decisions.

5.5 Conclusions

Strategies for sustainable resource recoveries from the treatment of CWW (377.83 t/h) + CB (7.29 t/h) wastes in CSFs (210 t starch/d), beyond conventional thermal energy + liquid biofertilizer recovery (Case I), were demonstrated. Integration of associated CS wastes (14.32 t/h) from cultivation fields into the waste treatment enables expansions in resource recoveries to include bioelectricity (31.96 MW- Case II; 9.63 MW- Case III) and usable water (372.85 t/h, Case III). Reuse of the recovered water for CHP in waste conversion (III) may reduce freshwater demands by 66%. Case II demonstrated potential to generate adequate thermal energy (starch drying air) and net power (~29 MW, > 2.17 MW needed in CSFs), hence, promising energy self-sufficiency in CSFs. Feasibility of total in-house energy supply for Case III will, however, require CS supplies in excess (86%) of available capacities of the farms that supply cassava to the CSF.

The economic assessment suggested all Cases (I-III) were economically viable (NPV, US$ 83.4 million-130 million) when the existing cost of CWW+CB treatment for disposal is taken into account. Projected MEPs for Case II bioelectricity ($0.0502-0.0534/kWh) revealed opportunities for cheaper power supply compared to grid power ($0.107/kWh). Hence, the conversion of the wastes could ensure sustainable process energy supply and expansions in profits through sales of surplus power. Active onsite waste conversions in CSFs can, therefore, promote sustainable environmental and economic developments in cassava starch industries.

6 Feasibility of commercial waste biorefineries for cassava starch industries: Techno-economic assessment

Chapter summary

Chapter 6 discusses the commercial feasibility of the five advanced integrated cassava starch wastes [7.29 t/h DM CB + 377.83 t/h CWW + 450.89 t/h CS] biorefinery schemes hypothesized in the present study (section 3.2.2.2; applicable to Specific Objective 3, section 1.3). The schemes include: (I) CB + CWW biogas plus CS to produce CHP, (II) CB+CWW for producing bioethanol and 100% of CS by-passed to CHP, (III) CS+CB+CWW for bioethanol with 90% CS by-passed for CHP production, (IV) CS+CB+CWW for co-production of GS, bioethanol and CHP with 90% CS by-passed to CHP production, (V) CS+CB+CWW for co-production of SA, bioethanol and CHP with 90% CS by-passed for CHP production. The commercial feasibility was analyzed through Aspen Plus process simulations and economic assessments. The key finding revealed that only the scenarios (I)-(II) are profitable for viable economic investments in the starch industries. Economic sensitivity analysis showed that, for all scenarios (I-V), changes in the working capital had little impact on the profitability and vice-versa for the electricity & feedstock price, total production costs, and fixed capital investments. The study (Chapter 6) therefore contributes to knowledge on the potentials for and risks to investments in advanced biorefinery conversions of the cassava starch wastes for implementation decisions.

The Chapter 6 was written according to the format of the **Bioresource Technology (Elsevier journal)** and has been published in same*:*

***Padi RK**, Chimphango A., 2020. Feasibility of commercial waste biorefineries for cassava starch industries: Techno-economic assessment. Bioresour Technol; 297: 122461 (Published online).*

Declaration by the candidate:

With regard to Chapter 6, pg. 120-149, the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution
Defining the scope of the study, conceptualizing the cassava wastes biorefinery (CWB) schemes, Aspen Plus simulations and economic assessments of the CWBs, analyzing and interpreting results, writing of the manuscript.	85 %

The following co-authors have contributed to Chapter 6, pg. 120-149:

Name	E-mail address	Nature of contribution	Extent of contribution
Chimphango, A.	achimpha@sun.ac.za	Assisted in defining the scope of the study, conceptualization of the CWB schemes, general discussions, and reviewed manuscript.	15 %

Signature of candidate: ……………….

Date: ………………………………..

Declaration by co-authors:

The undersigned hereby confirm that:

1. The declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 6, pg. 120-149

2. No other authors contributed to Chapter 6, pg. 120-149, besides those specified above, and

3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 6, pg. 120-149, of this dissertation.

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Feasibility of Commercial Waste Biorefineries for Cassava Starch Industries: Techno-economic Assessment

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Abstract

Cassava waste is a potential bioresource for integrated biorefineries to co-produce bioproducts [succinic acid (SA), glucose syrup (GS), bioethanol] and combined heat and power (CHP). Techno-economic assessments of five biorefinery scenarios for integration in cassava starch plant (200 Mg/d), co-processing 377.83 Mg/h wastewater (CWW), 7.29 Mg/h bagasse (CB) and 450.89 Mg/h stalks (CS), were done using Aspen Plus® to ascertain their potential commercial viability. Scenarios (I) & (II) co-process CB+CWW for biogas and bioethanol production, respectively, and CS for CHP. Scenario (III)-(V) co-process CB+CWW+10% CS for bioethanol (III), co-producing either GS (IV) or SA (V) and 90% CS for CHP. All scenarios meet CHP demands for biorefinery and starch processing. However, only Scenario (V) products had their minimum selling prices equal to market prices. Thus, integration of SA production (6.9 Mg/h) in a biorefinery co-producing bioethanol and CHP is a potential viable cassava waste biorefinery with economic and environmental benefits.

Keywords: Bioethanol; Cassava starch processing; Combined heat and power; Integrated cassava wastes biorefinery; Succinic acid

6.1 Introduction

The industrial processing of cassava (*Manihot esculenta*) into starch is energy intensive, with thermal energy and electricity consumptions ranging from 1.6-2.5 MJ and 0.17-0.25 kWh per kg of processed starch, respectively [177]. Notably, most cassava growing areas are characterized by limited and expensive energy supply, which limit advancements and new investments in the cassava industry. For instance, energy for cassava starch processing (CSP) constitutes 14% of production cost in Thailand [44] and 20-25% in Nigeria [12]. Therefore, sustainable energy supply is essential for advancement of the cassava industry.

The cassava industry generates lignocellulosic residues including cassava stalks (CS) from harvesting of the cassava roots, rasped pulp + peel termed cassava bagasse (CB) and large volumes of wastewater (CWW) from CSP. The CS is estimated at 63% of the cassava root mass [175]. Large proportions of CS are left in the field as waste [71], whereas, a small proportion, about 10-20% of the total CS, are used as planting materials [100]. The CS contains 22-39% starch of the dry matter [100], which can be recovered for high value products. The CB from the CSP has 85 wt.% moisture content, which constitutes a major challenge for sustainable storage, handling and disposal [89]. In addition, the CSP demands large amounts of water, estimated at ~18 m^3 per ton, resulting in generation of CWW up to 20 m^3 per ton starch [44]. The wastewater contains starch, which is a loss from the starch process. Starch losses of 0.157 kg per m^3 CWW have been estimated [44], which contributes to typical organic loadings of 8.0-66.2 kg COD/m^3,[51]. Thus, the CWW is a major water pollution concern.

The high starch contents and high production rates of the CS, CWW and CB wastes, motivates biorefinery exploits [51,100], thus the co-production of valuable bio-products and bioenergy from the wastes. The cassava waste can be converted to biogas and/or bioethanol from the CS, CWW and CB [109,176,183]. In addition, there is potential for producing high-value bio-products such as succinic acid (SA) and glucose syrup (GS) [51,108]. The cassava waste-based biorefineries can be a gateway to achieving the much needed cassava industrial expansions and sustainable energy supply for the starch processing.

The SA and its derivatives such as tetrahydrofuran, are used extensively in the plastic, polymer, pharmaceutical, surfactants, and detergent industries [48,49]. It is projected that the bio-based SA market could contribute nearly 58% of the global market of US$ 191 million per annum [49]. Similarly, GS is the largest derivative market for the starch industry with a compound annual growth rate of 4.2% [75]. The rising demand of the GS is attributed to the growth in the pharmaceutical and convenience food sectors where GS serves as a major raw material [75]. However, the techno-economic feasibility of the combined cassava waste biorefineries for commercial applications have not yet been explored [51]. The uncertainty surrounding the techno-economic feasibility for the biorefinery routes is therefore a foreseeable limitation to the implementation of the cassava waste biorefineries.

Techno-economic assessments (TEA) involving simulations of processes and financial models using established experimental or technical data and advanced simulation software such as Aspen Plus®, is a well-developed tool that has been extensively applied in technology or process feasibility assessments. TEA modelling has been widely applied in various bioenergy or biorefinery feasibility studies and found adequate for process and economic feasibility demonstrations [57,173]. Similar modelling based on TEA demonstrations could help establish the techno-economic feasibility for the prospective cassava biorefineries.

This study evaluated the technical and economic feasibility of cassava waste biorefineries for integration in cassava starch processes. The study addressed two major questions, thus, (1) whether the cassava waste based biorefineries can generate sufficient energy (thermal + electricity) for self-use while meeting the energy demands of a ‘host’ 200 Mg/d cassava starch facility [71] under profitable conditions, and (2) what product diversification in the biorefinery is economically feasible. Therefore, biorefineries involving various combinations of CWW, CB, and CS as feedstock to co-produce various combinations of bioproducts comprised of bioethanol, SA, GS, and combined heat and power (CHP) have been considered. The technical feasibility was assessed through process flowsheet simulations in Aspen Plus® using laboratory data reports on mass conversions. The economic feasibility was evaluated relative to minimum expected selling prices (MESP) and Net Present Value (NPV), using the year 2018 fiscal conditions of South Africa as a model developing economy for the cassava cultivation regions. Investment risks assessment was carried out by means of sensitivity analysis, aimed at establishing the profitability impacts of changes in essential economic parameters, such as total production costs.

6.2 Methods

6.2.1 Process design and simulations

6.2.1.1 Conceptualized process scenarios

Motivations for the development of cassava starch waste-based biorefineries include reducing water use and pollution burdens, and increasing energy supply for the starch industries [71]. Therefore, five (5) biorefinery scenarios were conceptualized targeting zero wastewater and solids disposal. In addition, the feasible feedstock capacities, laboratory biomass conversions and efficiencies, and the commercial status of requisite technologies were considered. Detailed process description for each scenario follows in section 6.2.1.3.

6.2.1.2 Production capacity and feedstock supply

The biorefinery plant is assumed to be an annex to a ‘host’ 842 Mg/d cassava processing plant producing 200 Mg/d cassava starch [44,71]. The host plant supplies the CB and CWW to the biorefinery, which are augmented with varying fractions of CS recovered from the fields. Pertinent to the CS supplies, average cassava production capacities of Ghana at 14.49 million Mg/a [5] and average CS-to-cassava production ratios at 0.63 [175] were considered. It was presumed that only 40% of the total CS generated is available for the biorefinery because 10-

20% of the generated CS is used as planting materials and some fraction is used as combustion fuels [100]. The biorefinery throughput was thus projected at 7.29 Mg/h CB (dry mass) [44], 377.83 Mg/h CWW [176], and 450.89 Mg/h CS (at 25% moisture).

6.2.1.3 Process descriptions

6.2.1.3.1 Scenario (I): Combination of cassava bagasse and cassava starch waste water for biogas production and cassava stalks for producing combined heat and power

Scenario (I) (Fig. 6-1a) comprises anaerobic digestion (AD) of the CWW+CB (38.4 kg/m^3 TS) to biogas, followed by treatment of the AD effluent to usable water and dried sludge. The biogas and dried sludge augment the CS (450.89 Mg/h) as fuel in the CHP. The AD system and performance were adopted from Luo et al. [260], demonstrating ~85% COD removal for a cassava ethanol stillage (30-80 kg/m^3 TS) at an organic loading rate of 11.3 kg COD/m^3.d and hydraulic retention time (HRT) of 5 days. The biogas yield was projected at 0.22 m^3 CH_4/kg COD removed, and the effluent's volatile fatty acid-VFA (acetic + propionic acids) was specified at 0.035 kg/m^3 [260].

The AD effluent is aerobically digested, followed by reverse osmosis (RO) treatment [57]. The treated water is recycled as process water whereas the brine solution from the RO is evaporated to 50% g/g salts using a multiple effect evaporator for onward incineration in the CHP [57]. The sludge from AD + aerobic digestion (~79.5% g/g moisture) is centrifuged and air dried (40% g/g moisture) to enhance co-combustion with the biogas + dried sludge + CS [278]. A steam drum boiler equipped with a live-bottom grate combustor generates high pressure steam (60 atm, 454°C) which is fed to a condensing turbine. The turbine drives the generator to produce power and the exhaust steam is fully condensed, deaerated and recirculated to the boiler as feed water. The exhaust flue gas passes through an economizer for heat exchange with the air necessary for starch drying (170°C, 3257 kJ/kg starch) [261]. The flue gas is desulfurized with a lime solution (20% g/g), followed by baghouse filtration prior to discharge into the atmosphere [57].

6.2.1.3.2 Scenario (II): Combination of cassava bagasse and cassava wastewater for production of bioethanol with all cassava stalks used for production of combined heat and power

Scenario (II) (Fig. 6-1b), involves enzymatic hydrolysis (EH) of the CB+CWW, fermentation of the hydrolysate for ethanol production [183], and AD of the generated wastewater. The derived biogas + solids are augmented with the CS for the CHP [57]. The EH was based on a one-step approach, involving simultaneous addition of Liquozyme® SC DS (0.2% g/g), Spirizyme® Fuel (0.066% g/g), and Novozyme® NS 50012 (0.4% g/g), that demonstrated advantages of higher sugar yields, lower temperature and residence time than the conventional two-step liquefaction + saccharification [183]. The envisaged industrial scheme is a separate hydrolysis and fermentation (SHF) process. The CB+CWW (38.4 kg/m^3 TS) is dewatered to 30% TS (g/g) [57], then heated to 50^{o}C for the EH [183], via steam (13 atm, 268°C) injection [57]. The EH scheme involves addition of the enzyme cocktail to the feed via an in-line mixer, followed by distribution into 24h batch reactors [57,183]. The temperatures of the EH reactors are controlled by a cooling water system.

The ethanologen *Zymomonas mobilis (Z. mobilis)* was selected for the bioethanol fermentation due to advantages of low sugar metabolism to cell mass and ability to co-ferment glucose (hexose, C6) and xylose (pentose, C5) efficiently [57,60]. The fermentation scheme developed by the National Renewable Energy Laboratory- NREL [57] was presumed. The hydrolysate is cooled to 32°C, and split into 10% and 90% for the seed production and the fermentation respectively [57]. Phosphorous and nitrogen nutrients for seed growth are supplied by diammonium phosphate (DAP) and corn steep liquor (CSL) at respective loadings of 0.67 g/L broth and 0.5% (g/g) [57]. Similarly, DAP and CSL are added to the fermenter at respective loadings of 0.33 g/L and 0.25% (g/g) [57]. The fermentation system involves 36h batch fermenters. The seed production and fermentation temperature is controlled using chilled water [57].

The bioethanol recovery/purification section consists of two distillation columns (beer and rectification), and a molecular sieve adsorption unit (MSAU) [57]. The beer column separates CO_2 from the fermentation broth as the overhead stream. Accompanying ethanol losses are recovered, via a water scrubber, and returned to the column. Insoluble solids in the bottoms stillage are separated by means of a pressure filter, followed by reduction of the moisture to 35% by air drying for fuel applications in the CHP. The liquid filtrate is sent to the wastewater treatment (WWT) section. The rectifier dehydrates a 40% ethanol side-draw from the beer column to 92.5% g/g ethanol overhead and 0.05% g/g ethanol bottoms. The bottom is sent to the WWT. The overhead vapor is further dehydrated to the 99.5% ethanol vapor in the MSAU, and then condensed for storage. The WWT and CHP operations are similar to Scenario (I)'s (section 6.2.1.3.1**)**, however, an extraction-condensing steam turbine (ECST) replaces the condensing turbine to facilitate steam extraction (13 atm) for the EH heating demand.

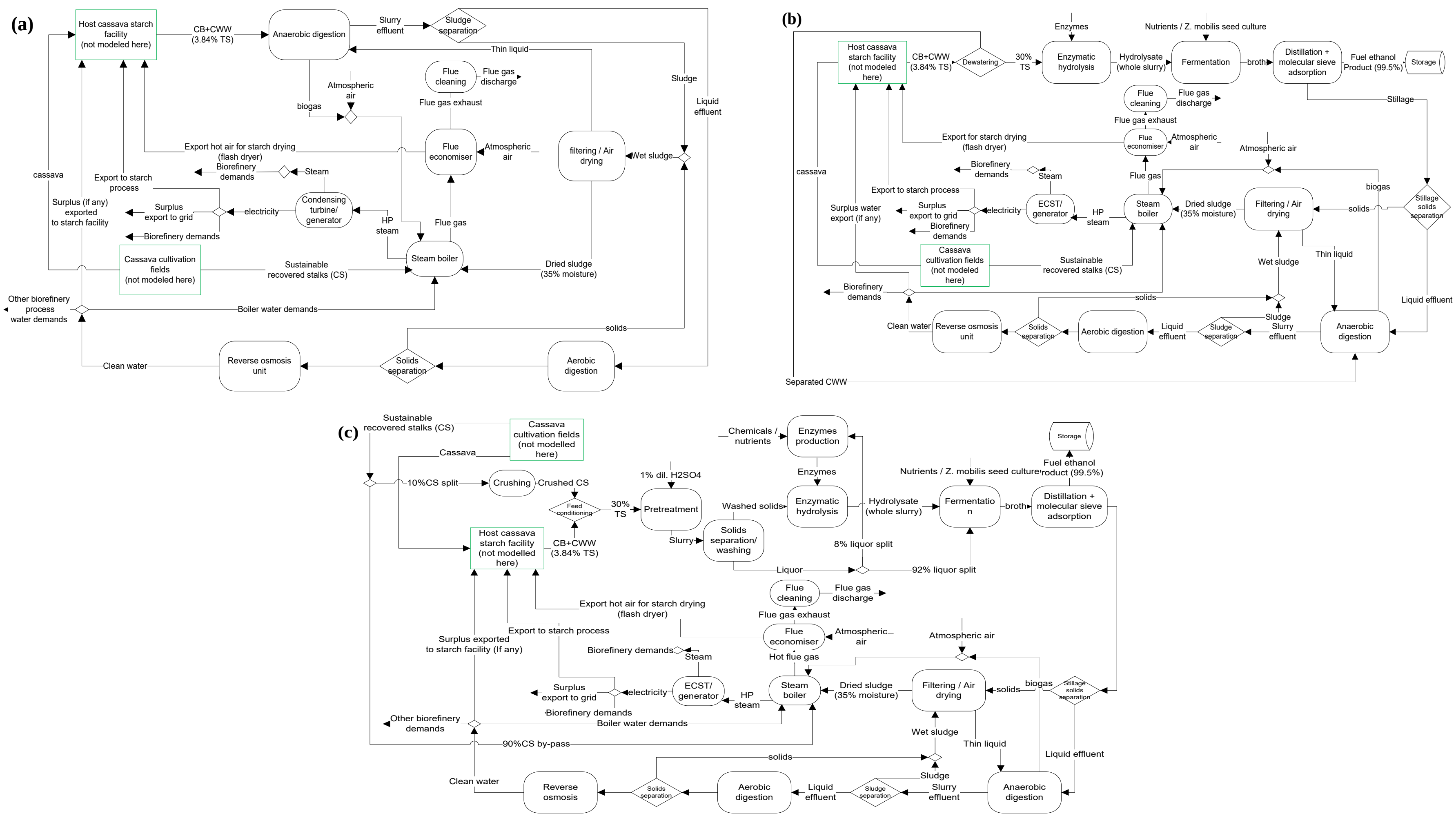

Fig. 6-1: Cassava waste biorefineries integrated in cassava starch processing - (a) Scenario I [CB+CWW+CS for producing CHP]; (b) Scenario II [CB+CWW for producing bioethanol & CS for CHP]; (c) Scenario III [CS (10%)+CB+CWW for producing bioethanol & CS (90%) for CHP]. Where TS = total solids, CS = cassava stalks, CB = Cassava bagasse, CWW = Cassava starch wastewater and CHP = Combined Heat and Power & ECST = extraction-condensing steam turbine.

6.2.1.3.3 Scenario (III): A combination of 10% of cassava stalks, cassava bagasse and cassava wastewater for bioethanol production with 90% of the cassava stalks used for combined heat and power production

In Scenario (III) 10% of the total CS is added to the CB+CWW for bioethanol and on-site enzyme production (Fig. 6-1c). The woody nature of the CS necessitates pretreatment to facilitate optimal conversion of the starch and cellulose/hemicellulose to ethanol. Studies have shown favorable acid pretreatment, with dilute H_2SO_4 projected as promising for commercial operations [57,109]. Thus, the experimental work reported by Martín et al. [109], was adopted, but presuming a 30% TS loading to reduce the ethanol recovery energy demands [57].

The CS is first crushed in a hammer mill then mixed with CB+CWW (~77% water), followed by dewatering to 51% water [44]. The mixture is preheated to 100°C via controlled direct hot water (rectifier bottoms) and steam injection (13 atm, 268°C) in a vertical pre-steamer [57] to ensure a TS of 30% g/g [57]. The heated slurry is acidified by 1% H_2SO_4 in a plug screw feeder then further heated to 170°C for 20 minutes using steam (13 atm, 268°C) in a pretreatment reactor [57,109]. The reactor discharges into a flash tank operated at 130°C [57]. The flashed vapor carries along most of the furfural (~99%) and HMF (~10%) inhibitors, thereby detoxifying the product. The slurry is conditioned with ammonia to a pH of 5 and 27% g/g solids [57]. To preserve the sugars and enhance EH, the pretreatment liquor is separated from the solids [109] then split for enzyme production (8%) and fermentation (92%) processes [57]. Water is added to the solids (~35.1 % TS) to facilitate the EH process.

An optimal EH process (86% glucans conversion to glucose) for a similar cassava peel substrate, involving 5% (v/w) cellulase + 10% (v/w) β-glucanase loadings at 50°C and 48h, is presumed [209]. The proposed on-site cellulase production scheme involves submerged aerobic cultivation of *Trichoderma reesei* fungi [57].

6.2.1.3.4 Scenario (IV): Combination of 10% of the cassava stalks, cassava bagasse and cassava wastewater for co-production of glucose syrup, bioethanol with 90% of the cassava stalks used for combined heat and power production

Commercial starch-based glucose syrup (GS) production employs acid-enzyme conversions [93], similar to the pretreatment and hydrolysis operations in Scenario (III). Hence, Scenario (IV) simulates use of the EH hydrolysate for GS production into Scenario III (Fig. 6-2a). The glucose-rich pretreatment liquor [109] is still designated for the bioethanol process due to the reducing sugar contents including xylose that can be co-fermented to ethanol by the *Z. mobilis* [60]. In the GS process, the hydrolysate is refined by separating the insoluble solids (protein, ash, fiber) using a centrifuge [93]. The insoluble solids are further washed to recover glucose losses [108], then air dried to 35% moisture [278] for use as boiler fuel. The filtrate passes through granular activated carbon at 70°C for adsorption of impurities such as HMF, thereby removing color and odor [93]. The GS is then concentrated to 70% [93] using a multiple-effect evaporator and steam (9 atm, 232°C) from the ECST [57,93], followed by cooling to 32°C for storage.

6.2.1.3.5 Scenario (V): Combination of 10% of the cassava stalks, cassava bagasse and cassava wastewater for co-production of succinic acid, bioethanol with 90% of the cassava stalks used for combined heat and power production

Scenario (V) models integration of succinic acid (SA) production into Scenario (III), using the EH hydrolysate as the carbon source (Fig. 6-2b). Based on reports of successful succinic acid production using high glucose concentration media (≥ 100 g/L) [134], the solids-free hydrolysate (150.74 g/L sugars) was considered for direct fermentation, while presuming similar process conditions and SA yields (0.82 g/g dry CB) as Sawisit et al. [137]. The SA process begins with centrifugation and detoxification of the EH hydrolysate in a manner similar to the GS process in section 6.2.1.3.4. Due to minimal nutrients requirements by *E. coli* [279], seed growth and SA fermentation nutrient demands are assumed similar to those described for *Z. mobilis* in section 2.1.3.2 [280]. The caustic (NaOH) added to the fermenter for pH control at 10 mol/L [280] reacts with succinate to form sodium succinate salts. Requisite CO_2 for seed growth and fermentation is supplied by the ethanol recovery section [104].

The fermentation broth is centrifuged to separate cell mass for recycle to the fermenter [281] then the cell-free broth is acidified with H_2SO_4 to lower the pH from 6.5 to 2.2, while forming neutralization products (sodium sulphate + water). This facilitates separation of the succinate, due to the incidence of approx. 99% succinate formation from the sodium succinate salts and its lower solubility at the pH of ~2 [281]. The succinate laden broth is concentrated in an evaporator, operated at 101°C and 1 atm [282], where most of the water and acetic acid are vaporized and condensed for treatment in the WWT. Further purification of the succinate is achieved via selective adsorption and crystallization operations, selected due to the derived benefits of high product yields and minimal energy demands [279,281]. In the adsorption stage, the zeolite bed (ZSM-5) with an adsorption affinity for only succinate, allows the salts + impurities to pass through in the liquid stream, which is treated in the WWT. Desorption of the zeolite bed with hot water (90°C) under vacuum [281] yields a pure succinate solution which is concentrated to saturation using an evaporator [281] operated at 90°C and 0.7 atm (Aspen predicted). The product is then crystallized by cooling to 4°C [282] followed by air drying to 98.1% pure SA product [281]. The residual liquor is returned to the zeolite adsorption column to recover SA losses.

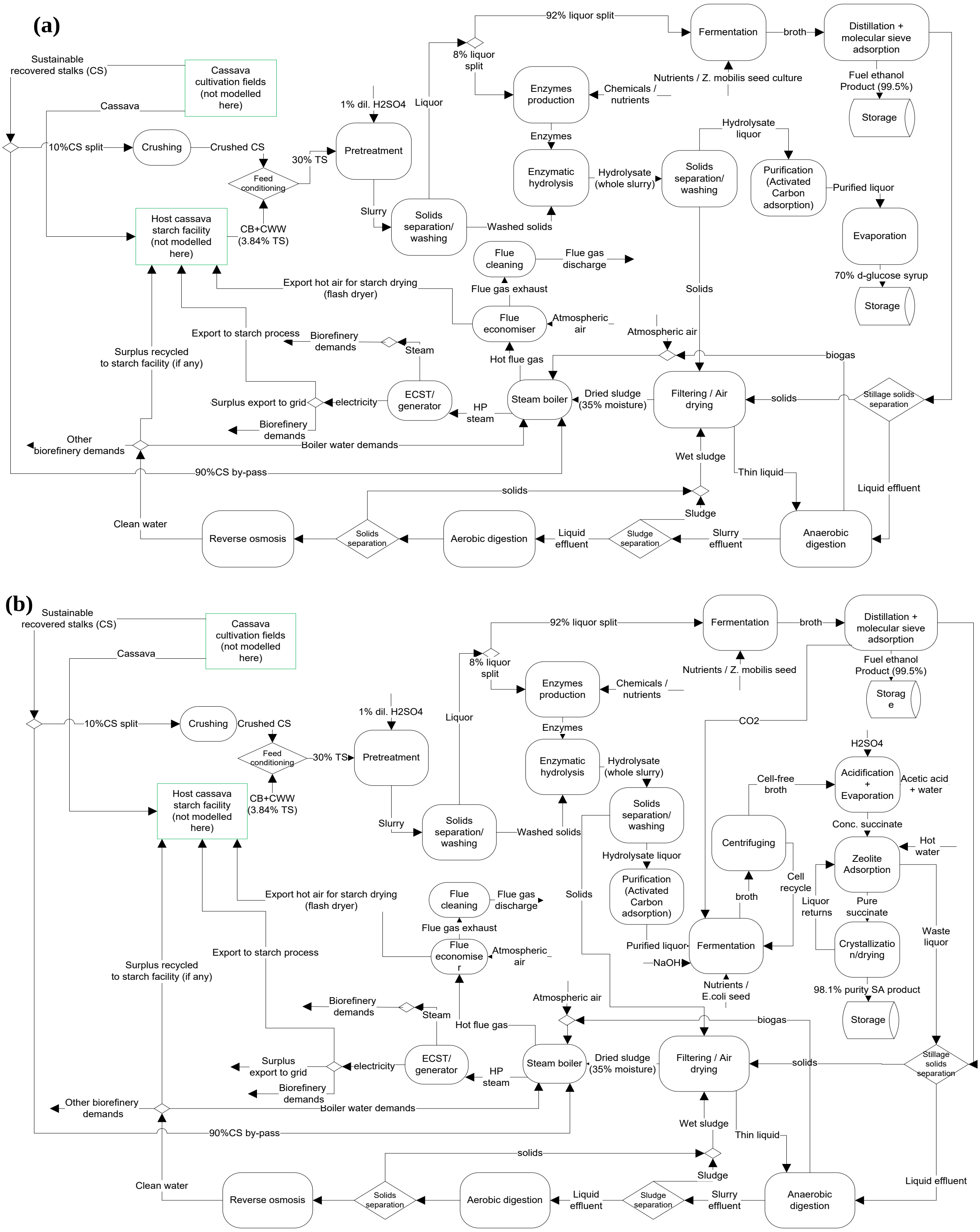

Fig. 6-2: Cassava waste biorefineries integrated in cassava starch processing- (a) Scenario IV [CS (10%) +CB+CWW for producing GS & bioethanol, and CS (90%) for CHP]; (b) Scenario V [CS (10%) +CB+CWW for producing SA & bioethanol, and CS (90%) for CHP]. Where TS = total solids, CS = cassava stalks, CB = Cassava bagasse, CWW = Cassava starch wastewater and CHP = Combined Heat and Power and SA = succinic acid.

6.2.1.4 Process simulation in Aspen Plus®

The mass and energy balances were executed by means of flowsheet simulation in Aspen Plus® v8.8 software (Aspen Technology, Inc., USA). Electrolyte Non-Random Two liquid (ELECNRTL) was selected as the general thermodynamic model [270]. This was modified to more suitable models for selected process sections, such as the Non-Random Two Liquid/Hayden-O'Connell (NRTL-HOC) for the pretreatment section [57], and steam property IAPWS-95 for the CHP section [266]. This is due to the fact that the ELECNRTL is more suited for electrolyte solutions with multiple solvents and high dissolved gases, which is not the case for the considered dilute acid pretreatment and CHP processes [57]. The major unit operations of pretreatment, hydrolysis, and ethanol/SA fermentations were modelled as stoichiometric reactors (Rstoic) using established stoichiometric reactions [57] and mass conversions based on various reports [57,109,137,183,209,280] (Appendix C, Table C.1). Similarly, the AD process was modelled using detailed stoichiometric reactions [57,263] and experimental findings [260]. Simulation of the enzyme production, GS process, product recovery/purification, WWT, and CHP systems follow similar models [57,265]. Additional process energy demands such as power for solids conveyors were estimated via calculator blocks based on various reports [57,108]. Power demand by the CS hammer mill was specified at 0.022 kWh/kg CS [108].

6.2.2 Economic modelling

6.2.2.1 Capital and production costs estimations

To estimate the total capital investments (TCI), the total installed equipment costs was estimated using the purchased equipment costs (PEC) and applicable installation factors [57,283]. The sizing and costing of the equipment were based on the mass and energy balance calculations from the process simulations (Table 6.1). Cost data for generic equipment such as pumps and storage tanks were obtained from the in-built Aspen Process Economic Analyzer in the Aspen Plus v8.8 software, while those for the specialized equipment such as the MSAU and pre-treatment reactor were obtained from vendors or literature quotes [57,265,268].

The cost data for equipment sizes or years other than this study's basis were adjusted using the exponential factors and the Chemical Engineering Plant Cost Index (CEPCI) based on various reports [57,269]. The total direct costs (TDC), including total installed costs, warehouses, additional piping, and site development, were projected at ~103 - 107% of the total installed costs, depending on the direct plant sections [57,265]. Total indirect costs (TIC), comprising contingencies, field + construction expenses, start-up costs and permits, were then estimated as 60% of the TDC [57,265]. The working capital (WC) was projected as 5% of the FCI [57,265]. The TCI is then determined as FCI + WC + land [265,269]. The estimated TCIs are presented in Table 6.2.

Total production costs (TPC) consist of total variable costs (TVC), total fixed costs (TFC), and plant overhead costs (POC) [269]. The TVC, comprising the costs of raw materials, process utilities, and waste handling charges, were estimated based on various reports and local utility costs presented in Table 6.3 (Appendix C, Table C.2). The TFC includes the costs of labor, labor burden (90% of labor costs), equipment depreciation, and maintenance (2% of PEC), while the POC comprises property insurance + tax (0.7% of FCI) and annual income tax [57,265]. A linear equipment depreciation involving zero salvage value and 20 years recovery period was assumed [265,266]. Annual income tax rate was set at 28% [266] and was charged on only positive net revenue [265]. Table 6.3 presents the breakdown of the estimated TPCs (see detailed in Appendix C, Table C.2).

Table 6.1: Mass and energy balance of the cassava waste biorefinery scenarios for integration into cassava starch processing

Process results	Units	Scenarios				
		I	II	III	IV	V
Mass parameters						
CWW	Mg/h	377.83	377.83	377.83	377.83	377.83
CB (dry mass)	Mg/h	7.29	7.29	7.29	7.29	7.29
CS (25% moisture)	Mg/h	450.89	450.89	450.89	450.89	450.89
Treated water from WWT	Mg/h	491.28	514.15	1968.56	2040.33	1907.32
Process make-up water	Mg/h	1570.21	1179.56	1715.29	1597.76	1697.39
Bioethanol	Mg/h	-	1.478	8.955	5.722	5.722
Glucose syrup	Mg/h	-	-	-	9.287	-
Succinic acid	Mg/h	-	-	-	-	6.908
Energy/utilities						
High pressure steam (60 atm, 454ºC)	Mg/h	1393.85	1393.66	1467.37	1477.26	1509.48
Pre-treatment/feed heating steam (13 atm, 268°C) [a]	Mg/h	-	13.5	30.53	31.02	30.97
Steam for GS evaporation (9.5 atm, 232°C)	Mg/h	-	-	-	27.761	-
Steam for SA evaporation (9.5 atm, 232°C)	Mg/h	-	-	-	-	58.764
Cooling water (28°C) [b]	Mg/h	62867.2	64015.9	82302.7	82791.4	80277.9
Export hot air for starch drying (170 °C)	Mg/h	185	185	185	185	185
Gross electricity generated	MW	335.39	327.78	200.17	243.15	236.43
Net electricity (excluding starch process demands)	MW	303.07	289.20	123.39	166.47	163.58

NB: The specified rate of production in the simulations was per hour basis. CWW- cassava wastewater, CB- cassava bagasse, CS- cassava stalks, GS- glucose syrup, SA-succinic acid, CHP- combined heat and power, WWT- wastewater treatment; [a] Pre-treatment steam applies to Scenarios III, IV, V and feed heating relates to Scenario II; [b] Total cooling water for chiller, fermentation and enzyme production systems (used in a cycle with minimal losses). Scenario I [CB+CWW+CS for CHP]; Scenario II [CB+CWW for bioethanol & CS for CHP]; Scenario III [CS (10%) +CB+CWW for bioethanol & CS (90%) for CHP]; Scenario IV [CS+CB+CWW for GS and bioethanol & CS (90%) for CHP]; Scenario V [CS (10%) +CB+CWW for SA and bioethanol & CS (90%) for CHP]

Table 6.2: Total capital investments (TCI) for the cassava waste biorefinery scenarios for integration into cassava starch processing

Cost components	**Scenarios (Million US$)**				
	I	**II**	**III**	**IV**	**V**
Installed costs- Plant sections					
Feed handling/conditioning [a]	55.328	55.328	57.158	57.158	57.158
Pre-treatment	-	-	18.863	18.863	18.863
Neutralisation/conditioning	-	0.146	61.483	61.438	61.358
Hydrolysis & fermentation	-	21.382	24.684	24.168	24.704
Onsite-enzyme production/conditioning	-	0.028	16.498	16.498	16.498
Ethanol-product recovery/purification	-	3.806	14.356	7.054	7.047
Wastewater treatment	53.862	53.877	120.313	122.902	137.139
Materials/product storage	1.877	1.622	2.421	1.864	1.853
CHP	191.118	190.391	181.645	187.095	188.208
Utilities systems (cooling + chilled water, process water + air, clean-in-place, fire hydrant) [b]	11.502	12.342	16.457	14.898	15.414
Glucose syrup purification [c]	-	-	-	0.626	-
Glucose syrup- solid separation + concentration [d]	-	-	-	17.032	-
C6 hydrolysate purification for succinate fermentation	-	-	-	-	2.554
Succinate fermentation	-	-	-	-	20.040
Succinic acid recovery/purification	-	-	-	-	9.696
Installed capital costs (ICC)	**313.687**	**338.922**	**513.878**	**529.596**	**560.532**
Warehouses (A)	2.213	3.228	7.722	8.114	8.717
Site developments (B)	4.980	7.262	17.374	18.255	19.613
Additional piping (C)	2.490	3.631	8.687	9.128	9.806
Total direct costs-TDC (Installed costs + A + B + C)	**323.370**	**353.043**	**547.661**	**565.093**	**598.668**
Total indirect costs- TIC (60% of TDC)	**194.022**	**211.826**	**328.596**	**339.056**	**359.2**
Fixed Capital investment- FCI (TDC + TIC)	**517.392**	**564.868**	**876.258**	**904.149**	**957.869**
Land [e]	1.848	1.848	1.848	1.848	1.848
Working capital- WC (5% of FCI)	25.870	28.243	43.813	45.207	47.893
TCI (FCI + Land + WC)	**545.110**	**594.960**	**921.918**	**951.204**	**1007.61**

[a] Includes cassava stalks (CS) crushing (where applicable) and total CS storage; [b] The clean-in-place facility supplies hot sterilization/cleaning chemicals to the hydrolysis, fermentation, enzyme production, and distillation systems; [c] Design based on Kwan et al. [185]; [d] Estimated as the cost of the biochemical sugar model's saccharification + sugar concentration section ($19624087) minus cost of the ethanol model's saccharification reactor + pump ($11499471) by Humbird et al. [57]; [e] Assumed area of 50 ha [57]. Scenario I [CB+CWW+CS for CHP]; Scenario II [CB+CWW bioethanol & CS for CHP]; Scenario III [CS (10%)+CB+CWW for bioethanol & CS (90%) for CHP]; Scenario IV [CS (10%)+CB+CWW for GS and bioethanol & CS (90%) for CHP]; Scenario V [CS (10%)+CB+CWW for SA and bioethanol & CS (90%) for CHP]. CS = cassava stalks, CB = Cassava bagasse, CWW = Cassava starch wastewater & CHP = Combined Heat and Power

6.2.2.2 Profitability assessments

The profitability of the biorefineries was assessed based on two indicators: 1) Net Present Value (NPV), and 2) Minimum Expected Selling Prices (MESP). The NPV discounts all future cash flows over the plant's lifetime (30 years) to present values, under conditions of selling all the products at the market prices in Table 6.3. The MESP refers to the price of a major product (ethanol, electricity, glucose syrup, or succinic acid) that ensures an NPV of zero when the discount rate equals the expected Internal Rate of Return (IRR) of 9.7%, under conditions of set market prices for the co-products in the scenario (Table 6.3). To estimate the NPV and MESP, the capital costs, production costs and revenues over the plant life are incorporated in a discounted cash flow analysis (DCFA) (see Appendix C, Fig. C.1). The TCIs, TPCs, and revenues from product sales were used to develop a DCFA over the plant life. Furthermore, taking into account the environmental regulations and costs of industrial wastewater treatment and disposal [258], it was assumed that the biorefinery facility is paid for treating the CWW [185] (Table 6.3). An operational period of 24 h/d and design on-stream factor of 96% (i.e. 8410 h/a) was considered. A 40% equity and 60% loan finance scheme was assumed [57,265]. The loan term was specified at 8% interest and 10 years [265]. Discount rate and inflation rate at 9.7% (real term) and 5.7% respectively were considered in future monetary projections [266,270].

A 3-year engineering and construction period, having respective capital allocations of 10, 60 and 30%, and a 6-month start-up time was presumed [265,266]. Deviations in economic variables, including FCI, working capital, TPC, product prices, enzyme costs and feedstock costs, could impact the profitability, hence an avenue to investment risk. This investment risk was investigated through sensitivity analysis, involving assessments of the IRR responses to a ± 25% adjustment of the aforementioned variables.

Table 6.3: Annual total production costs (TPC) and revenues per cassava waste biorefinery scenario for integration into cassava starch processing

	Component	2018 prices (US$/kg, US$/kWh)	Scenarios (Million US$/a)					Reference(s)
			I	II	III	IV	V	
Production costs breakdown	Delivered feedstock	0.051	193.05	193.05	193.05	193.05	193.05	[266,270]
	Sulphuric acid (93%)	0.099	-	-	0.85	0.85	21.53	[265,266]
	Ammonia	0.442	-	0.0029	1.31	1.31	1.22	[265]
	Flue gas desulfuriser lime	0.092	0.10	0.10	0.76	0.75	0.78	[266]
	Boiler chemicals	6.917	0.02	0.02	0.28	0.28	0.28	[265]
	Cooling tower chemicals	4.145	0.44	0.45	0.57	0.58	0.56	[265]
	Corn steep liquor	0.079	-	0.0706	0.23	0.18	0.25	[265]
	Diammonium phosphate	0.382	-	0.04	0.12	0.09	0.13	[265]
	Glucose	0.853	-	0.1267	1.69	1.69	1.69	[265]
	Enzyme nutrients	1.138	-	0.00365	0.05	0.05	0.05	[265]
	Sorbitol	1.195	-	0.12	0.12	0.12	0.17	[57]
	Sulphur dioxide	0.082	-	0.00008	0.001	0.001	0.001	[265]
	Purchased enzymes	10.54	-	4.82	-	-	-	
	Activated carbon	0.6	-	-	-	0.44	0.44	[266]
	Caustic	0.105	3.17	3.20	4.43	4.59	4.49	[266]
	Waste disposal (mainly ash)	0.029	30.54	30.54	30.54	30.54	30.54	[57,266]
	Process make-up water	0.00022	2.91	2.18	3.17	2.96	3.14	[173,266]
	TVC (Total variable cost)		**230.23**	**234.73**	**237.17**	**237.48**	**258.32**	
	Total labour costs		0.80	1.05	1.29	1.37	1.46	
	Labour burden (90% of labour)		0.72	0.95	1.16	1.23	1.31	[57]
	Equipment depreciation		17.246	18.829	29.21	30.14	31.93	
	Maintenance (2% of Purchase Equipment Cost)		1.66	2.42	5.79	6.09	6.54	[57]
	TFC (Total fixed cost)		**20.426**	**23.249**	**37.45**	**38.83**	**41.24**	
	Property insurance + tax (0.7% FCI)		3.62	3.95	6.13	6.33	6.71	[57]
	Average annual income tax (28%)		31.00	27.92	0	8.17	24.89	[266]
	POC (Plant overhead cost)		**34.62**	**31.87**	**6.13**	**14.5**	**31.6**	
	TPC (Million US$/a)	TVC+TFC+POC	**285.28**	**289.84**	**280.75**	**290.81**	**331.16**	
Revenue breakdown	Sellable electricity (surplus)	0.1282	326.758	311.804	133.035	179.481	176.361	[266,270]
	Glucose syrup	0.6532	-	-	-	51.018	-	
	Ethanol product	0.985	-	12.032	72.912	46.588	46.586	[270]
	Succinic acid	2.7	-	-	-	-	156.869	[49,281]
	Export hot air for starch drying	0.0005	0.778	0.778	0.778	0.778	0.778	
	CWW treatment credit	0.0136	43.214	43.214	43.214	43.214	43.214	[258]
	Total revenues (Million US$/a)		**370.75**	**367.83**	**249.94**	**321.08**	**423.81**	

Scenario I [CB+CWW+CS for CHP]; Scenario II [CB+CWW for bioethanol & CS for CHP]; Scenario III [CS (10%)+CB+CWW for bioethanol & CS (90%) for CHP]; Scenario IV [CS (10%)+CB+CWW for GS and bioethanol & CS (90%) for CHP]; Scenario V [CS (10%)+CB+CWW for SA and bioethanol & CS (90%) for CHP]. Where CS = cassava stalks, CB = Cassava bagasse, CWW = Cassava starch wastewater, CHP = Combined Heat and Power

6.3 Results and discussions

6.3.1 Technical performance of the cassava waste-based biorefineries

The technical performances of the simulated cassava waste biorefineries (Table 6.1) show that all the scenarios have the potential to meet the energy demand for the biorefineries as well as that of the host starch process (200 Mg/d). In addition, there is a surplus of ~121-300 MW electricity, which is the net power shown in Table 6.1 minus the power needed by the starch process- ~2.17 MW electricity [177]. The potential surplus power projections in all the biorefinery scenarios suggest opportunities for energy self-sufficiency in the integrated cassava waste biorefineries annexed to a starch processing plant.

The consumptive power [calculated based on dry feedstock basis (kg DM)] for the Scenarios (I), (II), (III), (IV) and (V) translates to 0.09, 0.11, 0.22, 0.22, and 0.23 kWh/ kg DM, respectively (Fig. 6-3a). The results suggest that the co-production of bioethanol, GS, and SA approximately doubles the power demands when compared to the base scenario (Scenario I). About 335 MW gross power can be produced in the base scenario (Scenario I), where all the waste resources are dedicated to energy generation (Table 6.1). The predicted gross power translates to ~1 MWh/Mg DM, which is comparable to the predictions of 1.2 MWh/Mg DM for a sugarcane bagasse CHP for a sugar mill [284].

The bioethanol production was projected to be 1.478 Mg/h (Table 6.1) for Scenario (II), which translates into a yield of 0.20 g ethanol/g CB (or 0.394 g/g sugars). The yield is corroborated by findings of 0.21 g/g CB for a similar EH process using *S. cerevisiae* fermentation [181]. The power demands for the ethanol sections of Scenario (II) sums up to 3.67 kWh/kg ethanol, which is ~18-folds that of a cassava chip ethanol process estimated at 0.21 kWh/kg ethanol [285]. Likewise, the steam demands for EH in scenario (II) is relatively high. The heat conditioning of the cassava for production of bioethanol is estimated to be 12.96 kg/kg ethanol (at 3.62 MJ/kg steam) [285] versus 9.13 kg/kg ethanol (15.25 MJ/kg steam) in

Scenario (II) (Table 6.1). The high differences in the energy demand could be attributed to differences in the feed properties, starch & water contents, and the EH efficiencies (sugar titer), which have been shown to impact fermentation and distillation energy demands [57]. For instance, the power demand for fermentation and distillation in the cassava chip ethanol production are estimated at 0.04 and 0.02 kWh/kg ethanol, respectively [285], juxtaposed to that of Scenario (II) at 2.16 and 0.16 kWh/kg ethanol, respectively using data in Fig. 6-3a and Table 6.1. Improvements in the energy efficacies of the ethanol process for Scenario (II) could be focused on optimizing the EH to achieve higher sugar titer.

In Scenario (III), acid pretreatment and EH of the CB (7.29 Mg DM/h) + 10% CS (~33.82 Mg DM/h), generated reducing sugars (19.28 Mg/h, conc. of 165 g/L), which resulted in bioethanol production rate of 8.955 Mg/h (Table 6.1). This translates to a reducing sugar yield of 0.469 g/g DM, and ethanol yield of 0.218 g/g DM or 0.465 g/g sugars. The results are comparable to 0.502 g ethanol/g reducing sugars derived for a dilute acid pretreatment in combination with EH of CS [211]. However, the predicted 0.218 g ethanol/g DM is 2.18-folds higher compared to other feedstock such as wood bark [62], but is comparable to NREL's corn-stover (0.267 kg/kg DM) [57]. However, there was 1.23-folds difference in ethanol yields compared to the results by NREL's approach, which contributed to the differences in electricity demands at 0.01 kWh/mL and 0.001 kWh/mL ethanol for the NREL and Scenario (III), respectively (Fig. 6-3a).

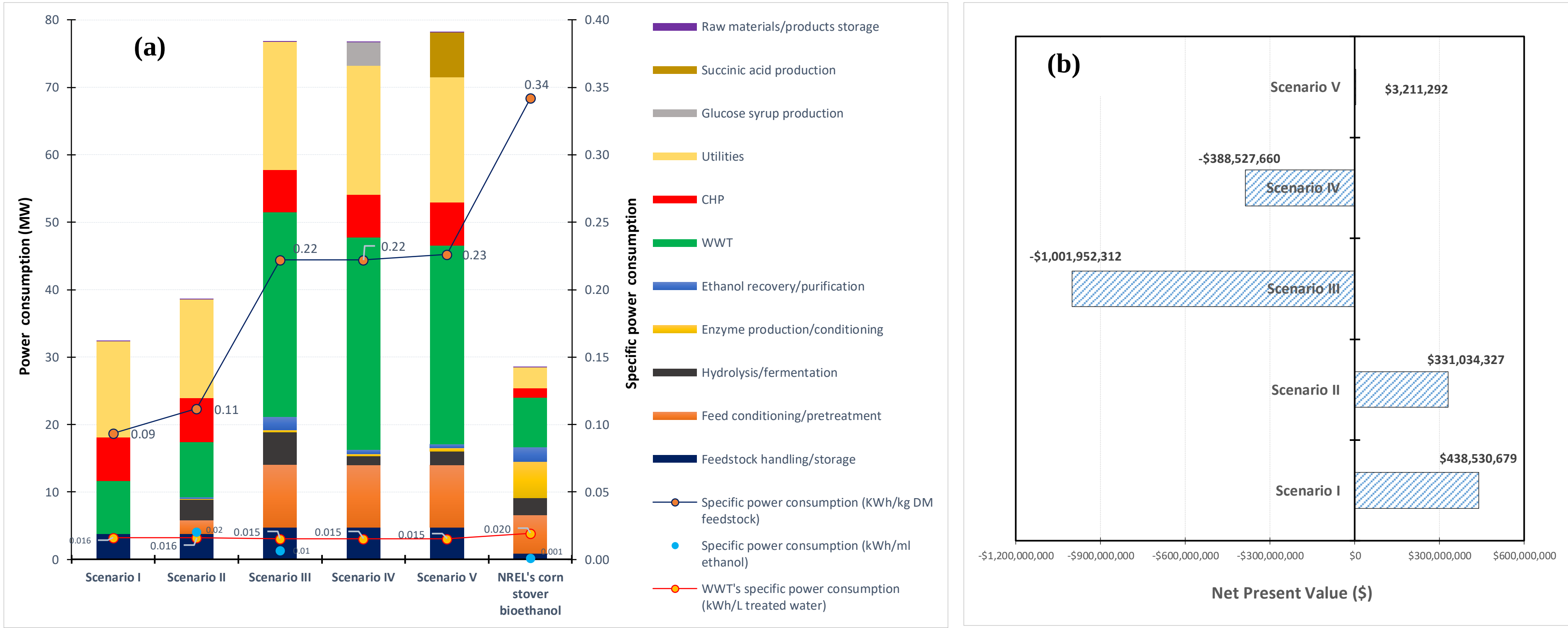

Fig. 6-3: (a) Electricity consumption per plant section of the cassava waste biorefinery scenarios (21383 kg/hr DM CS + CB) vs NREL's dilute acid pre-treated corn- stover bioethanol's (83330 kg/hr DM corn-stover; 22274 kg/hr ethanol) [57]; (b) Net Present Values (NPV) for the biorefinery scenarios [see Appendix C, Fig. C.1] . Scenario I [CB+CWW+CS for CHP]; Scenario II [CB+CWW for bioethanol & CS for CHP]; Scenario III [CS (10%)+CB+CWW for bioethanol & CS (90%) for CHP]; Scenario IV [CS (10%)+CB+CWW for GS and bioethanol & CS (90%) for CHP]; Scenario V [CS (10%) +CB+CWW for SA and bioethanol & CS (90%) for CHP]. Where DM = dry matter, CS = cassava stalks, CB = Cassava bagasse, CWW = Cassava starch wastewater, CHP = Combined Heat and Power, NREL= National Renewable Energy Laboratory, WWT = Wastewater treatment; FCI = Fixed capital investment, WC = Working capital, and TPC = Total production cost.

Relatively, high pretreatment steam (0.743 kg steam/kg DM) was predicted for Scenario (III) using data from Table 6.1, when compared to 0.337 kg steam/kg DM estimated by NREL [57]. The variation in steam generation could be explained by the differences in feedstock thermal properties and pretreatment conditions. For instance, the pretreatment temperature for Scenario (III) and NREL's approach were 170°C [109] and 158°C [57], respectively.

Based on the average content of glucans (73.15%) and hemicelluloses (8.7%) in the combined cassava waste [109,183], a theoretical maximum sugar yield of 0.912 g/g DM feedstock can be projected. Therefore, the yield of 0.469 g/g DM of reducing sugar represents ~51% of the theoretical value. Hence, there are opportunities to improve the efficiencies of the pretreatment and EH processes, which could in turn, enhance the process energy efficiencies [57].

Diversion of the EH hydrolysate (~6.747 Mg/h, 150.74 g/L reducing sugars) in Scenario (III) for the production of either GS (9.29 Mg/h) or SA (6.91 Mg/h), as simulated in Scenarios (IV) and (V), respectively, could lead to a reduction in the bioethanol production to 5.72 Mg/h (Table 6.1). The implications of the reduction in bioethanol production are reflected in the economic viability of the biorefineries. An annual production capacity of ~58 Gg for the SA can be projected for Scenario (V) with an assumption of annual operating hours of 8410 h/a. The predicted capacities for the SA (58 Gg/a) are within the range of industrial scale capacities of 10-30 Gg SA/a by industries such as Succinity, Reverdia, Myriant, and BioAmber and the targets of 70-200 Gg/a by BioAmber/Mitsui (North America) [49]. Therefore, the Scenario (V) biorefinery has a realistic commercial capacity vis-à-vis technology availability and sizes.

The power consumption in SA production (Scenario V) amounts to 6670 kW (Fig. 6-3a), which translates to ~966 kWh/ Mg SA. A process model of a similar SA scheme based on sugarcane bagasse pentoses [281] obtained a comparable electricity demand (1239 kWh/Mg SA), save for the contributions from feedstock handling and EH (Fig. 6-3a).

The integration of wastewater treatment and reuse in the cassava waste biorefineries can contribute to substantial reductions in fresh water consumptions, while mitigating associated environmental burdens. In all the scenarios (Table 6.1), water (491-2040 Mg/h) could be recovered as treated wastewater, which could supply 23.82%, 30.36%, 53.43%, 56.09% and 52.91% of total water demands (treated and process make-up) for Scenarios (I) to (V), respectively (Table 6.1). The cooling water demands for the Scenarios ranged between 62867 - 80277 Mg/h (Table 6.1) for a cycle. The predicted water losses (determined in Aspen) of approx. 2018, 1633, 2185, 2160 and 1142 Mg/h, for Scenarios (I) to (V), respectively, mainly occurred through evaporation from the cooling towers [57]. The losses have been accounted for in the process water make-up + treated water inputs (Table 6.1). Thus, the projected results show potential for reduced freshwater footprints for the biorefineries. In addition, it provides a strategy for treating wastewater generated from the starch process, hence, benefiting the environment.

6.3.2 Economic performances of the biorefineries

6.3.2.1 Capital and production costs estimates

The TCI for the scenarios ranged from US$ 545.11 million - US$1.01 billion, with Scenario (I) and Scenario (V) demonstrating the least and highest, respectively (Table 6.2). The projected installed capital cost (ICC) of ~US$ 314 million (Table 6.2) for the CHP (335 MW gross power) in Scenario (I) translates to 936 $/kW, which is in agreement with $500-2000/kW for biomass CHP technologies [274], when variations in capacities are considered. The CHP contributed the most to the ICCs, representing 60.92% Scenario (I), 56.18% (II), 35.5% (III), 35.33% (IV), and 33.58% (V) (Table 6.2; Appendix C, Fig. C.2). This is followed by the WWT and Biomass handling/storage at respective contributions of 17.17 & 17.68 % Scenario (I), 15.90 & 16.33% (II), 23.41 & 11.12% (III), 23.21 & 10.79% (IV), and 24.47 & 10.20% (V) (Table 6.1; Appendix C, Fig. C.2). Juxtaposing the ICCs for the CHP and WWT for Scenarios (I)-(V) (Table 6.2), to their respective gross electricity or treated wastewater (Table 6.1), a notable benefit of economies of scale could be inferred. For instance, at the gross power of 335.39 MW (I) and 200.17 MW (III) (Table 6.1), the ICCs for the respective CHPs translates to 569.8 $/kW and 907.5$/kW. The beneficial impacts of economies of scale is supported by the costs projections for biomass CHP and WWT technologies [258,274].

The annual projections for TPCs ranged from ~US$ 281 million – US$ 331 million (Table 6.3). Scenarios (III) and (V) showed the minimum and maximum TPC, respectively (Table 6.3). It is worth noting that the relatively low value for Scenario (III) could be attributed to the zero income tax projections (Table 6.3), as a result of the consideration of income tax charges on only positive net revenues. For the Scenarios (I) to (V), the TVCs represent 80.71%, 80.98%, 84.48%, 81.66%, and 78.01% of the respective TPCs (Table 6.3), suggesting significant impacts on the TVCs on the production costs. From the TVCs breakdown (Table 6.3), the delivered CS as feedstock, contributed the highest at 83.86% for Scenario (I), 82.20% (II), 81.40% (III), 81.30% (IV), and 69.72% (V). The findings are in agreement with assertions that the feedstock price is a major determinant factor of biorefinery or bioenergy production costs [173,274]. The CS cost of US$ 0.051/kg (Table 6.3) was based on energy equivalents of coal [270], which translates to US$3.13/GJ at an average calorific value of 16.3 MJ/kg [175]. The CS costs estimates compare well with feedstock price reports of 2.25-4 US$/GJ for large scale bioenergy systems [274].

6.3.2.2 Profitability and investment risks assessments

Relative to the NPVs, Scenarios (I), (II), (V) proved to be viable investments (positive NPVs), while Scenarios (III), (IV) demonstrated non-profitable outcomes (negative NPVs) (Fig. 6-3b). Scenario (III) exhibited the worst economic performance (Fig. 6-3b), suggesting the economic benefits derived from the increased ethanol production due to the additional C5 sugars is not high enough to justify the incurred pre-treatment costs. A biorefinery based on steam explosion pre-treated sugarcane residues, having a similar bioethanol capacity (7.48 Mg/h) as Scenario (III) (~8.96 Mg/h), while co-producing lactic acid (4.65 Mg/h) and surplus electricity (5.6 MW) was found economical [270]. Comparing the referred finding to Scenario (III)'s, it can be inferred that co-production of a higher-value product, such as the lactic acid at US$2/kg, could improve the biorefinery economics. Indeed, this was evidenced in Scenario (V), where co-production of the high-value SA enhanced the economics substantially, and even resulted in profitability (Fig. 6-3b). On the other hand, a sugarcane residues biorefinery having a comparable bioethanol capacity (5.7 Mg/h) to Scenario (IV)'s (~5.72 Mg/h), that co-produces furfural (2.07 Mg/h) and surplus electricity (7.5 MW), proved uneconomical [270]. The revenue from co-product furfural (~US$1.2/kg) was not high enough to absorb the additional investment costs, while supporting the bioethanol's investment for profitability. This inference supports and explains Scenario (IV)'s unviable investment considering the relatively low value (US$0.65/kg) and revenue contribution (15.9%, Table 6.3) of the co-product GS.

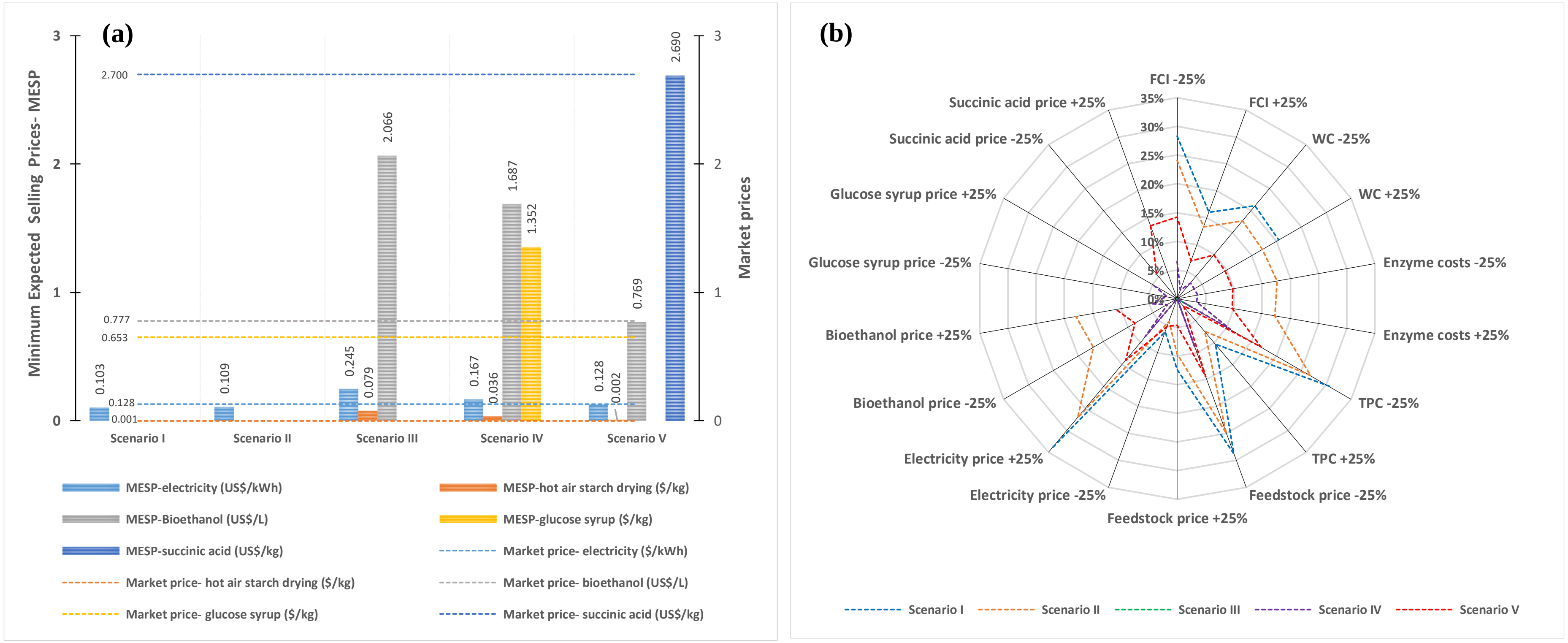

Fig. 6-4: (a) Minimum Expected Selling Prices (MESP) vs market prices of the major products per cassava waste biorefinery scenario; (b) Economic sensitivity analysis of the cassava waste biorefineries showing internal rate of return (IRR) for a 25% increase or decrease of selected economic variables. Scenario I [CB+CWW+CS for CHP]; Scenario II [CB+CWW for bioethanol & CS for CHP]; Scenario III [CS (10%) +CB+CWW for bioethanol & CS (90%) CHP]; Scenario IV [CS (10%) +CB+CWW for GS and bioethanol & CS (90%) for CHP]; Scenario V [CS (10%)+CB+CWW for SA and bioethanol & CS (90%) for CHP]. Where DM = dry matter, CS = cassava stalks, CB = Cassava bagasse, CWW = Cassava starch wastewater, CHP = Combined Heat and Power; FCI = Fixed capital investment, WC = Working capital, TPC = Total production cost.

For the MESP, relative to the market price (MP), reductions by 19.5% (I) or 14.8% (II), and increases by 91.4% (III) or 30.5% (IV) can be projected for electricity (Fig. 6-4a), while increments by 165.9% (III) or 117.1% (IV) were predicted for bioethanol (Fig. 6-4a). The projected GS MESP for Scenario (IV) is ~2-folds the MP (Fig. 6-4a). Based on the above MESPs for Scenarios (III) and (IV), the electricity provides a better opportunity to profitability enhancement than the bioethanol or GS. This could further be explained by the high contributions of surplus electricity sales to the total revenues; at 53.23% (III) and 55.91% (IV) (Table 6.3). Interestingly, for Scenario (V), the projected MESPs for all products (electricity, bioethanol, SA) matched the MPs, as depicted in Fig. 6-4a. Scenario (V) could be considered as a potential profitable scenario for integration of cassava waste biorefinery and cassava starch processing. Other technical and economic strategies such as optimized and cost-effective pre-treatment methods can improve the profitability of Scenario (V).

The investment risks in the five cassava waste-based biorefineries would arise from the electricity price, feedstock price, TPC and FCI. The investment risks and influential economic variables for the cassava waste-based biorefineries identified through sensitivity analysis involved comparison of IRRs for ± 25% deviations from the expected IRR of 9.7%. The analysis showed that the changes in the WC had the least impact on the economics for all scenarios (Fig. 6-4b). In Scenarios (I) and (II), the magnitude of the effects of the economic variables on profitability, in decreasing order, were electricity price > TPC > feedstock price > FCI (Fig. 6-4b). The 25% decrease in the electricity price for Scenario (I) and (II) results in IRRs of 5.15% and 4.67%, respectively, thus rendering the scenario economically unviable (Fig. 6-4b). Likewise, a 25% increase in the TPC renders Scenario II uneconomical (IRR of 7.44%). However, changes in feedstock price and FCI still render the Scenarios (I) and (II) profitable with IRR ≥ 9.7% (Fig. 6-4b). In contrast, Scenario (III) remained unviable with changes in all the economic variables (Fig. 6-4b). In Scenario (IV), with the exception of the

TPC reduction, the changes of all the other variables led to unprofitable outcomes with IRR< 9.7% (Fig. 6-4b). Furthermore, in Scenario (V), either reduction in product prices or increase in the FCI, TPC and feedstock price negates the profitability (Fig. 6-4b). The magnitude of the effects of the economic variables on profitability in Scenario (V), in decreasing order, were TPC > feedstock price > electricity price > SA price > FCI (Fig. 6-4b). The delivered feedstock costs accounts for approx. 58 - 69% of the TPCs (Table 6.3). Therefore, in order to minimize the investment risks, reductions in the feedstock prices could invariably reduce the TPCs. The feedstock costs can be reduced by improvements in crop yield, which can be achieved through application of advanced inputs such as high yielding cassava varieties [100]. Average cassava yields are estimated at 16.1 Mg/ha [5]. Nearly 447,000 ha of cassava cultivated area to obtain adequate CS for the scenarios. However, high mobilization and transportation costs of the CS can equally increase the CS price.

In the context of the FCI, the investment risks can be mitigated by provision of incentives, which could be in the form of tax exemptions [258,286], or motivating bioelectricity feed-in-tariffs [286]. In the cost estimates, the CHP and WWT sections contributed the most to the investment costs (Table 6.2). Investment and operation costs for CHP and WWT technologies vary depending on region specific variables, such as import taxes, local content policies, and environmental regulations [258,274], thus, prospective avenues for provision of government incentives that could lead to capital cost reductions.

Overall, Scenarios (I) and (II) are promising for near term implementation considering that CHP and EH bioethanol technologies are commercially mature technologies with extensive deployments in biorefineries. The C5 + C6 sugars-based biorefineries (Scenarios (III-V)) could derive economic benefits from integration of high-value co-products, such as SA. Technologies for production of bioethanol from both C5 and C6 sugars and for the production of SA are still in the initial stages of commercialization, with only few deployments reported for single production schemes [49]. Therefore, the findings of this study contribute to integrated biorefinery scenarios that could help overcome economic barriers associated with the single production schemes, such as the economic benefit of using the by-product carbon dioxide from the bioethanol fermentation for the SA fermentation.

6.4 Study limitations and recommendations

The conceptualization and simulations of the biorefineries were constrained by literature gaps. For example, there is no optimized pre-treatment and EH of CS, CB or blends. Pre-treatment agents such as alkali and steam explosion show better performance for various biomass substrates than the dilute acid used in this study. Reducing sugars from a dilute alkali pre-treated pinus wood bark were ~3-folds higher than from pretreatment with dilute acid [62]. Furthermore, steam explosion demands lower thermal energy than dilute acid pre-treatment [113], thus, the lower energy and higher sugar yields, imply higher productivities that could potentially improve the economics of the biorefinery. However, some biomass substrates show detrimental responses to various pre-treatment methods [217], thus compatibility and optimized performance of the various pre-treatments should be investigated for the cassava wastes.

In Scenario (V) in which SA is produced, a simultaneous saccharification and fermentation (SSF) process can be applied to reduce end-product inhibition and capital costs, when compared to the SHF in this study [283]. For instance, a high solids loading (116.8 g/L cassava starch) SSF process for SA production using *E. coli* and cassava starch substrate proved successful with an achieved product yield of 0.86 g SA/g starch [134]. Such performance is similar to the performance achieved in Scenario (V), thus, 150.74 g/L sugars with SA yields of 0.82 g/g DM. Feasibility of a similar SSF scheme is therefore envisaged for Scenario (V), and should be experimentally investigated as it could lessen the FCI and improve the profitability. Furthermore, the considered adsorption-crystallization process for the downstream SA recovery/purification is a proposed scheme based on experiences in sugar mill industries [281]. The feasibility and performance must therefore be experimentally verified for further improvement of the simulations, especially the efficacy of the ZSM-5 zeolite for the SA adsorption [281].

6.5 Conclusions

The potential economic viability of the cassava waste biorefineries, for same conversion technology, depends largely on product/ feedstock combinations. Conversion of CB, CS and CWW can generate CHP that is enough for operating integrated cassava starch process and waste biorefineries. Furthermore, co-production of CHP with bioethanol and SA in a biorefinery, has potential economic benefits. In addition, use of the CWW as a co-feedstock is a viable strategy for reducing freshwater footprint in the biorefinery. Thus, the paper has unveiled sustainable approaches to commercialization of cassava waste biorefineries with environmental and economic gains to the cassava starch industries.

7 Comparative sustainability assessments for integrated cassava starch wastes biorefineries

Chapter summary

Chapter 7 addresses the comparative environmental impacts and sustainability (environmental + social + economic) assessments of the simulated cassava wastes biorefineries in Chapter 6, and the business-as-usual wastes treatment (BAU) as a baseline scenario (Specific Objective 4, section 1.3). The assessments were achieved via in-depth environmental life cycle simulations for the processes in SimaPro (using inventory data from the in-depth Aspen Plus® process simulations in Chapters 5 & 6), and a Percentage Sustainability Index (PSI) tool custom-built for two perspectives of decision makers [(i) mutual investor-environmentalist, (ii) investor]. The results suggest the CWBs demonstrate higher environmental benefits than the BAU when avoided impacts from equivalent fossil-based products are taken into account. The PSI assessments revealed the scenarios (I)-(II) favor the economic dimension of sustainability , and the BAU, (III)-(V) favor the environment dimension.

The Chapter 7 was written according to the format of the **Journal of Cleaner Production (Elsevier journal)** and has been published in same**:**

Padi, RK, Chimphango, A. *Comparative Sustainability Assessments for Integrated Cassava Starch Wastes Biorefineries. J Clean Prod; 125171 (published online)*

Declaration by the candidate:

With regard to Chapter 7, pg. 152-190, the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution
Defining the scope of the study, conceptualizing the sustainability metrics for the biorefineries, SimaPro LCA simulations, analyzing and interpreting results, writing of the manuscript.	87 %

The following co-authors have contributed to Chapter 7, pg. 152-190:

Name	E-mail address	Nature of contribution	Extent of contribution
Chimphango, A.	achimpha@sun.ac.za	Contributed to the scope definition, assisted with suggestions, general discussions, revised & proof-read manuscript.	13 %

Signature of candidate: …………………

Date: ………………………………..

Declaration by co-authors:

The undersigned hereby confirm that:

1. The declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 7, pg. 152-190

2. No other authors contributed to Chapter 7, pg. 152-190, besides those specified above, and

3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 7, pg. 152-190, of this dissertation.

Signature	Institution	Date
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Comparative Sustainability Assessments for Integrated Cassava Starch Wastes Biorefineries

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Abstract

Sustainable development in cassava starch industries is hampered by high cost and environmental burdens associated with the business-as-usual (BAU) waste management strategies. In BAU, starch wastewater & bagasse wastes are anaerobically digested to produce biogas for starch drying with the digestate getting disposed into watercourses while the cassava stalks are burnt. Converting the wastes into high-value bio-products in an integrated cassava wastes biorefinery (CWB) could enhance the economic exploitation while reducing the environmental burdens of the wastes. Five simulated CWBs and the BAU have been assessed and compared using simulations in SimaPro and a percentage sustainability index (PSI) estimation tool to identify product integration schemes that support the development of sustainable CWBs. The CWB scenarios included (I) combined heat & power, with (II) hexose-bioethanol, (III) pentose & hexose-bioethanol, (IV) pentose-bioethanol + glucose syrup, and (V) pentose-bioethanol + succinic acid. The environmental impacts generally increased with the number of product integrations within the biorefinery gate boundaries. However, accounting for avoided emissions from the corresponding fossil-products, the CWBs show higher emission savings than the BAU. The PSIs for the CWBs show that scenarios (I)-(II) favor the economic dimension over the environment dimension and vice versa for scenarios

(III)-(V) and the BAU. Thus, the CWBs (I) and (II) may be explored for their potential to enhance sustainable industrial developments in cassava starch industries.

Keywords: Bioethanol; Environmental impacts; Integrated biorefineries; Integrated cassava starch wastes; Life cycle sustainability assessments; Succinic acid

7.1 Introduction

Growing demands for cassava (*Manihot esculentum*) starch in industrial applications (e.g. pharmaceuticals, food) resulted in expanded cassava cultivation (~ 292 million t/a) and starch processing [5]. However, high costs and environmental burdens associated with waste management and energy sources in cassava starch industries (CSI) hamper sustainable industrial developments [23,51,72]. The cassava starch facilities (CSF) generate large amounts of cassava starch wastewater (CWW) and cassava bagasse waste (CB), with respective generation capacities at 12-20 m^3 and 1.4 t (35-40% moisture) per t starch produced [44]. Crop harvesting also generates woody cassava stalks (CS) estimated at 51% of the cassava roots by mass, which are mainly designated as wastes with only 10-20% used as planting materials [82]. In the current wastes management scheme [business-as-usual (BAU)], the CB and CWW are anaerobically digested to generate biogas for producing starch drying hot air (SDHA), followed by disposal of the digestate into watercourses [73]. The CS are openly burnt in the farms [82]. Electricity for the CSF operations and waste treatment (~90-260 kWh/t starch) is fossil-based [73,177]. Consequently, high water & land pollution, carbon footprints, and waste treatment & energy costs pose limitations to sustainable developments in the CSIs [23,51,72].

Substitution of fossil-based energies & products with biomass-based alternatives is accelerating sustainable low carbon economies based on the promising economic and environmental benefits revealed in previous reports [49,287]. Use of the edible cassava roots as feedstock for bioenergy production [first generation (1G) bioenergy] has been advocated because of high yields of starch [288,289]. Various studies have shown environmental benefits of the cassava-based 1G bioethanol vs. the fossil alternatives [285,289]. However, because of the prevalent food uses for the cassava root starch [32], the use of the cassava residues as feedstock for second generation (2G) bioenergy is preferable for sustainable co-production of food (starch) and bioenergy, especially for regions with declining arable lands [80]. Laboratory and pilot demonstrations have shown possibilities for converting the CWW, CB & CS to high-value bio-products such as bioethanol, succinic acid, glucose syrup and combined heat and power (CHP) [50,51,108]. Thus, there is potential for the development of industrial-scale multi-product biorefineries for integration into cassava starch processing, potentially enhancing economic exploitations of the wastes and industrial developments in the CSIs. Sustainability of industrial developments calls for potential maximum tri-dimensional value extraction from the applied resource's entire life cycle, including economic, environmental and social values [290]. Hence, based on the various aspects of the sustainability concept, the idea that biorefineries are fundamentally sustainable, due to the renewability and environmental savings (CO_2 sequestration) potentials of the biomass feedstock, is subject for debate [149,291].

The sustainability concept, therefore, promotes developments having three-dimensional fundamental stability (3D)- economic, environmental and social, termed Triple Bottom Line (TBL) sustainability [54,292]. However, separate and different assessment methodologies as well as indicators where the concept is limited to one dimension (1D) (e.g. economic, social) or two dimensions (2D) (e.g. socio-environmental, socio-economic) exist [54]. The 1D & 2D assessments are too limited to inform sustainability decisions as the performance of each dimension is essential to various stakeholder priorities such as investors (economic), employees (economic & social) and government/policy makers (social & environmental) [47,54]. Globally, several sustainable development policies are shifting towards the 3D criteria. An example is the proposed framework for transitioning from Millennium Development Goals (MDGs) to Sustainable Developments Goals (SDGs) in the '2030 Agenda for Sustainable Development' [56]. Consequently, studies have emphasized the need to incorporate 3D sustainability in biorefinery designs and implementations, attentive to related impacts such as food security, environmental pollution, energy security, and socio-economic impacts [47,54].

Specifically, incorporating sustainability evaluations in biorefinery designs could facilitate identification of hotspots for improvements, and the selection of sustainable product integration schemes from possible options [47,54].

Discrepancies in sustainability indicators dominate current sustainability discussions, attributed to the lack of standardized methodologies [47,54,67]. For example, the reliance of the social aspect on opinions of diverse stakeholders (e.g. investors, policy makers) with different priorities introduce subjectivity in the outcome [293,294]. Nevertheless, some methodologies under development allow for adaptations for context-specific objectives and have proven useful for biorefinery implementation decision support. Life Cycle Sustainability Assessment (LCSA) is one such example, which has been advocated for decision-making towards more sustainable products or processes [67]. The LCSA methodology supports the evaluation of environmental, social and economic impacts of the considered process or product along the entire value chain or under equal boundary specifications for purposes of comparing projects [65–67]. LCSA has been applied in waste biorefinery designs for some industries, such as the sugar mill industry [295,296]. Nieder-Heitmann et al. [296] for instance, applied LCSA to rank the sustainability of sugarcane bagasse & trash based biorefineries producing bioenergy only, bioenergy integrated with succinic acid, itaconic acid, or polyhydroxybutyrate & succinic acid. Conversely, little has been done for the biorefineries based on wastes from CSIs, thus, hampering their adoption.

Potential economic benefits from integrated cassava starch wastes biorefineries (CWB) over BAU's must not be pursued at the expense of higher environmental burdens and socio-economic detriments [297]. Thus, environmental burden mitigation and sustainability enhancement strategies must be considered in process designs and CWB products selection. The need for the 3D approach for the CWB calls for preliminary performance assessments to identify possible sustainable CWB scenarios, as well as identification of hotspots in the CWBs for prospective improvements. Therefore, in this study, the environmental burdens and the sustainability of five innovative CWB concepts and the BAU have been assessed and compared, to provide preliminary decision support frameworks for product integration schemes that can support development of sustainable CWBs. The CWB schemes incorporate innovative circular economy (CE) strategies, i.e. revitalization of products or resources after their end-of-life or functional life for reuse as raw materials rather than treated as waste [292], as possible TBL sustainability enhancement schemes in the CSIs. The innovative CE strategies involve total recovery & conversion of field wastes (CS) & process wastes (CWW+CB) into alternate products [bioethanol, glucose syrup, succinic acid, CHP] potentially supporting synergistic enhancements in economic, environmental and total in-house (CSF & CWB) energy provisions in CSIs. The incorporated CE strategies, therefore, promote sustainability measures regarding prudent and extended usage of the CSI's resources [292]. The comparative LCSA was done using a percentage sustainability index (PSI) tool, custom-built for two perspectives of decision makers: (i) mutual investor-environmentalist perspective and (ii) investor perspective. The findings contribute to sustainable CWB process schemes that will advance investment decisions and applications in CSIs.

7.2 Description of the conceptualized cassava starch wastes biorefineries

The CWW and CB feedstock capacities for the studied scenarios were specified based on generation capacities for typical 200 t starch/d CSF, while the CS feedstock was projected based on feasibility demonstrations for the CWBs in a previous study [298]. The CWW, CB, and CS feedstock were, thus, specified at 377.83 t/h [176], 7.29 t DM/h [44], and 450.89 t/h [298], respectively. The baseline conventional wastes management scheme to be compared with the CWB scenarios is presented in section 7.2.1. The process descriptions for the proposed CWB scenarios (Fig. 7-1) have been presented in the previous study [299] (Chapter 6), thus only summarized in sections 7.2.2 (see Table 7.1).

7.2.1 Conventional management scheme for the cassava starch wastes (Business-As-Usual (BAU) scenario)

The BAU scenario (Fig. 7-2a) describes the prevailing approaches to handling the cassava starch wastes (summarised in Table 7.1). The process involves AD of the CWW (377.83 t/h) + CB (7.29 t DM/h) wastes to generate biogas for SDHA, followed by disposal of the effluent (digestate) into watercourses [72,73]. On the other hand, the CS (450.89 t/h) disposal simply involves gathering and open burning in the wild [82]. Thus, in the eLCA simulations, environmental loadings of the CWW+CB digestate are designated as emissions to water, while gaseous and solid emissions from the SDHA system (Fig. 7-2a) are designated as air emissions and landfill disposal respectively. For the open burning of the CS, complete combustion was assumed, where all gaseous emissions are designated as emissions to air, and the solid particulates (such as ash) are allocated to land emissions (Fig. 7-2a).

7.2.2 Proposed cassava wastes biorefinery schemes

The proposed CWBs are same as the biorefineries in the previous work in Chapter 6, thus, the processes follow the descriptions for the scenarios (I)-(V) in section 6.2.1.3 (Process descriptions), summarized below:

- Production of combined heat and power from cassava stalks integrated with biogas from cassava starch wastewater and bagasse (Scenario I) (detailed in Fig. 7-2b)
- Integration of cassava starch wastewater and bagasse based ethanol production with stalks based combined heat and power (Scenario II) (detailed in Fig. 7-3)
- Conversion of cassava starch wastewater, bagasse and 10% stalks to bioethanol and in-house enzyme integrated with 90% cassava stalk based combined heat and power production (Scenario III) (elaborated in Fig. 7-4)

- Co-production of glucose syrup and bioethanol from conversion of cassava starch wastewater, bagasse and 10% stalks, integrated with 90% stalk based combined heat and power production (Scenario IV) (illustrated in Fig. 7-5)
- Co-production of succinic acid and bioethanol from conversion of cassava starch wastewater, bagasse and 10% stalks, integrated with 90% stalk based combined heat and power production (Scenario V) (illustrated in Fig. 7-5)

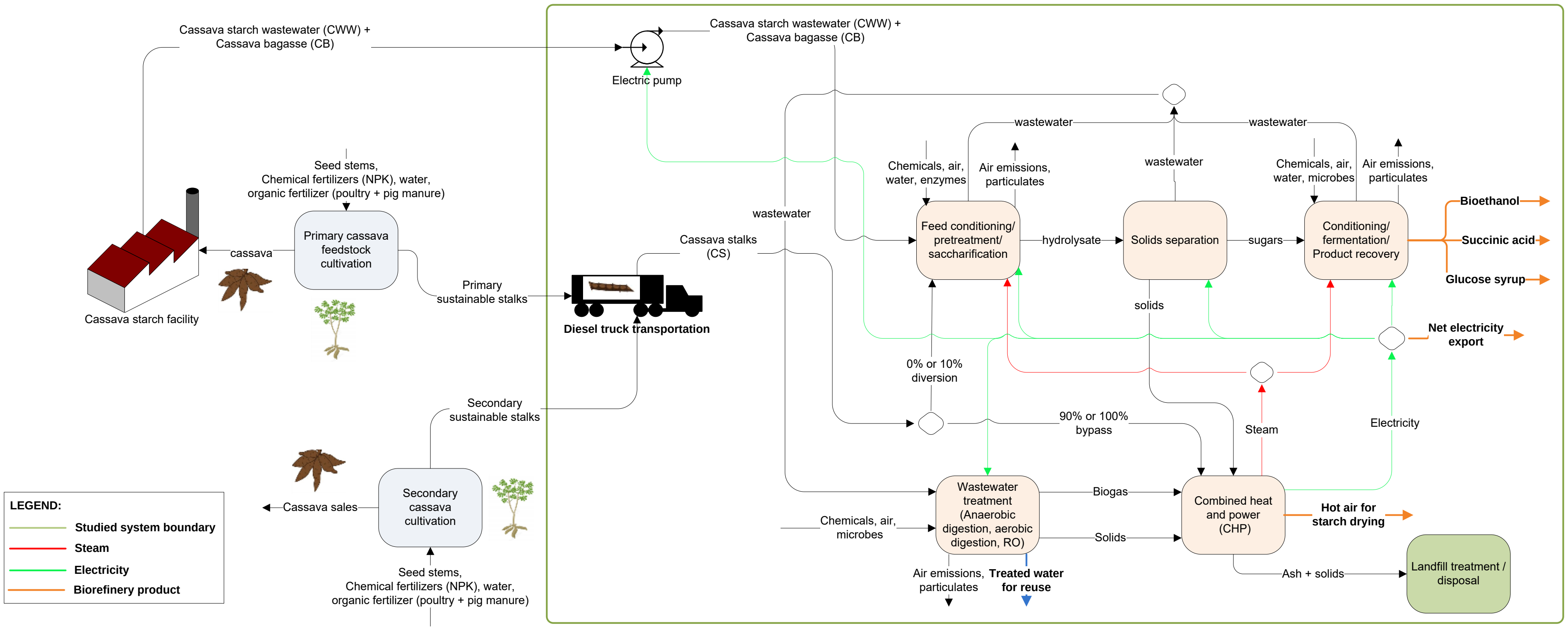


Fig. 7-1: Simplified diagram showing the system definitions and boundaries of integrated cassava waste biorefineries

Table 7.1: Summary of the cassava wastes biorefinery scenarios

Biorefinery scenarios	Feedstock inputs/h	Process description	Products recovered/h	Reference(s)
Business-as-usual (BAU)	377.83 t cassava starch wastewater (CWW) + 7.29 t cassava bagasse (CB) + 450.89 t cassava stalks (CS)	Anaerobic digestion of CWW+CB for biogas for hot air production & open burning of CS; Process electricity (360 kW) sourced from coal-based grid power	185 t starch drying hot air- SDHA (170 °C); 1.34 t surplus biogas	[298,300]
(I)	377.83 t CWW + 7.29 t CB + 450.89 t CS	CWW+CB biogas plus CS converted to combined heat and power (CHP); energy self-sufficient process	185 t SDHA; 303.07 MW electricity	[298]
(II)	377.83 t CWW + 7.29 t CB + 450.89 t CS	CWW+CB for producing bioethanol and 100% CS by-passed to CHP; Enzymatic hydrolysis (EH) pre-treatment of CB; energy self-sufficient process	185 t SDHA + 289.2 MW electricity + 1.478 t bioethanol	[298]
(III)	377.83 t CWW + 7.29 t CB + 450.89 t CS	CS+CB+CWW for bioethanol with 90% CS by-passed for CHP production; dilute acid + EH pre-treatment of CB+CS; energy self-sufficient process	185 t SDHA + 123.39 MW electricity + 8.955 t bioethanol	[298]
(IV)	377.83 t CWW + 7.29 t CB + 450.89 t CS	CS+CB+CWW for co-production of GS, bioethanol and CHP with 90% CS by-passed to CHP production; dilute acid + EH pre-treatment of CB+CS; energy self-sufficient process	185 t SDHA + 166.47 MW electricity + 5.722 t bioethanol + 9.287 t glucose syrup	[298]
(V)	377.83 t CWW + 7.29 t CB + 450.89 t CS	CS+CB+CWW for co-production of SA, bioethanol and CHP with 90% CS by-passed for CHP production; dilute acid + EH pre-treatment of CB+CS; energy self-sufficient process	185 t SDHA + 163.58 MW electricity + 5.722 t bioethanol + 6.908 t succinic acid	[298]

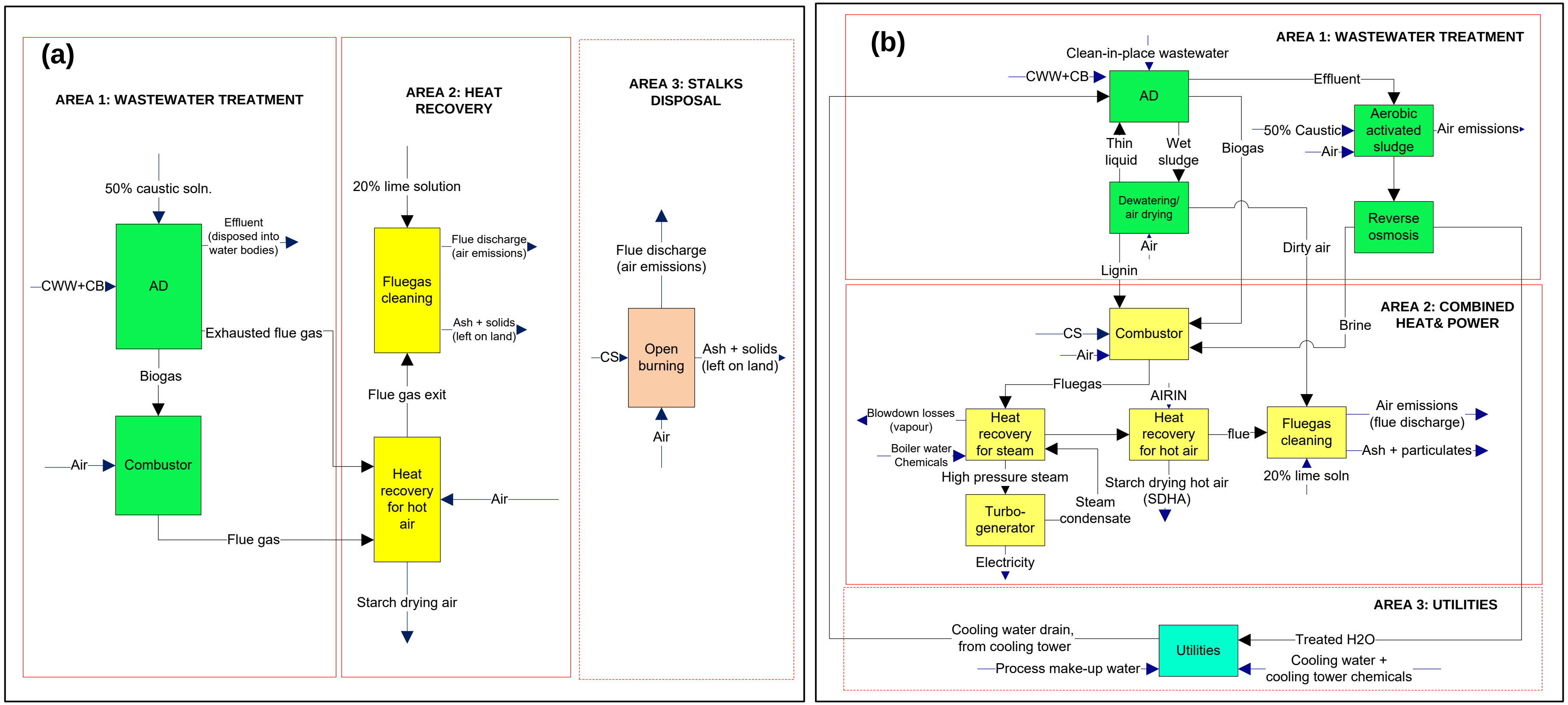


Fig. 7-2: Schematic diagram of the cassava waste conversion/disposal systems. (a) Anaerobic digestion (AD) of cassava starch wastewater (CWW) and bagasse (CB) for biogas based starch drying hot air generation, plus open burning (disposal) of cassava stalks- CS (field wastes) [BAU scenario]. (b) Production of combined heat and power (CHP) from CS integrated with biogas from CWW+CB [scenario (I)] [Adapted from [298]]

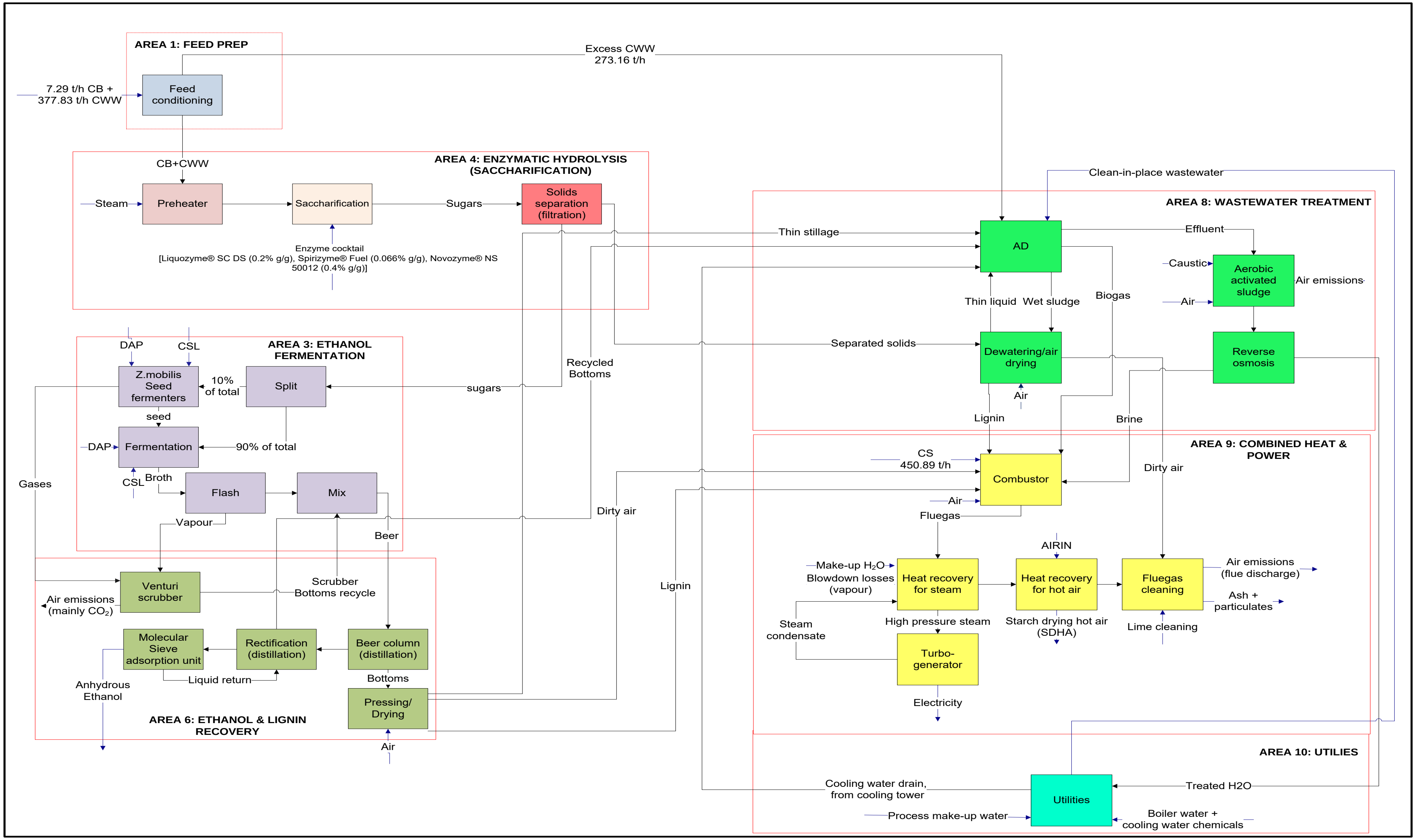


Fig. 7-3: Schematic layout of the cassava starch wastes biorefinery co-producing bioethanol from integrated cassava starch wastewater and bagasse, and combined heat and power (CHP) from cassava stalks [scenario (II)] (Adapted from [298]). In the diagram, DAP = diammonium phosphate, CSL = corn steep liquor, AD = anaerobic digestion, CWW = cassava starch wastewater, CB = cassava bagasse, CS = cassava stalks

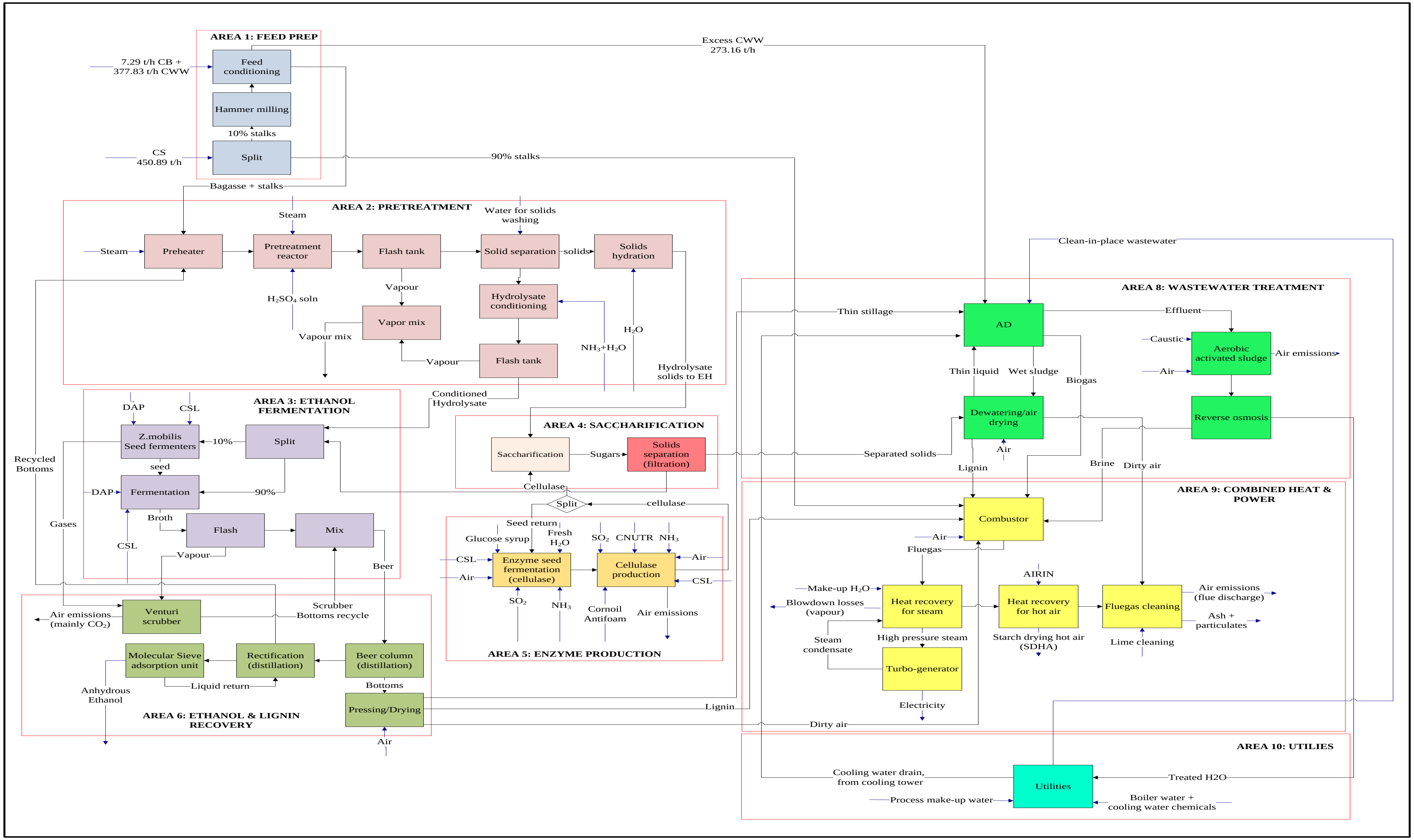


Fig. 7-4: Schematic diagram of the cassava starch waste biorefinery co-producing bioethanol from integrated CWW+CB & 10% CS, and combined heat and power (CHP) from 90% CS [scenario (III)] (Adapted from [298]). In the diagram, AD = anaerobic digestion, CB = cassava bagasse, CNUTR = Cellulase nutrient mix, CS = cassava stalks, CSL = corn steep liquor, CWW = cassava starch wastewater, DAP = diammonium phosphate, EH = enzymatic hydrolysis

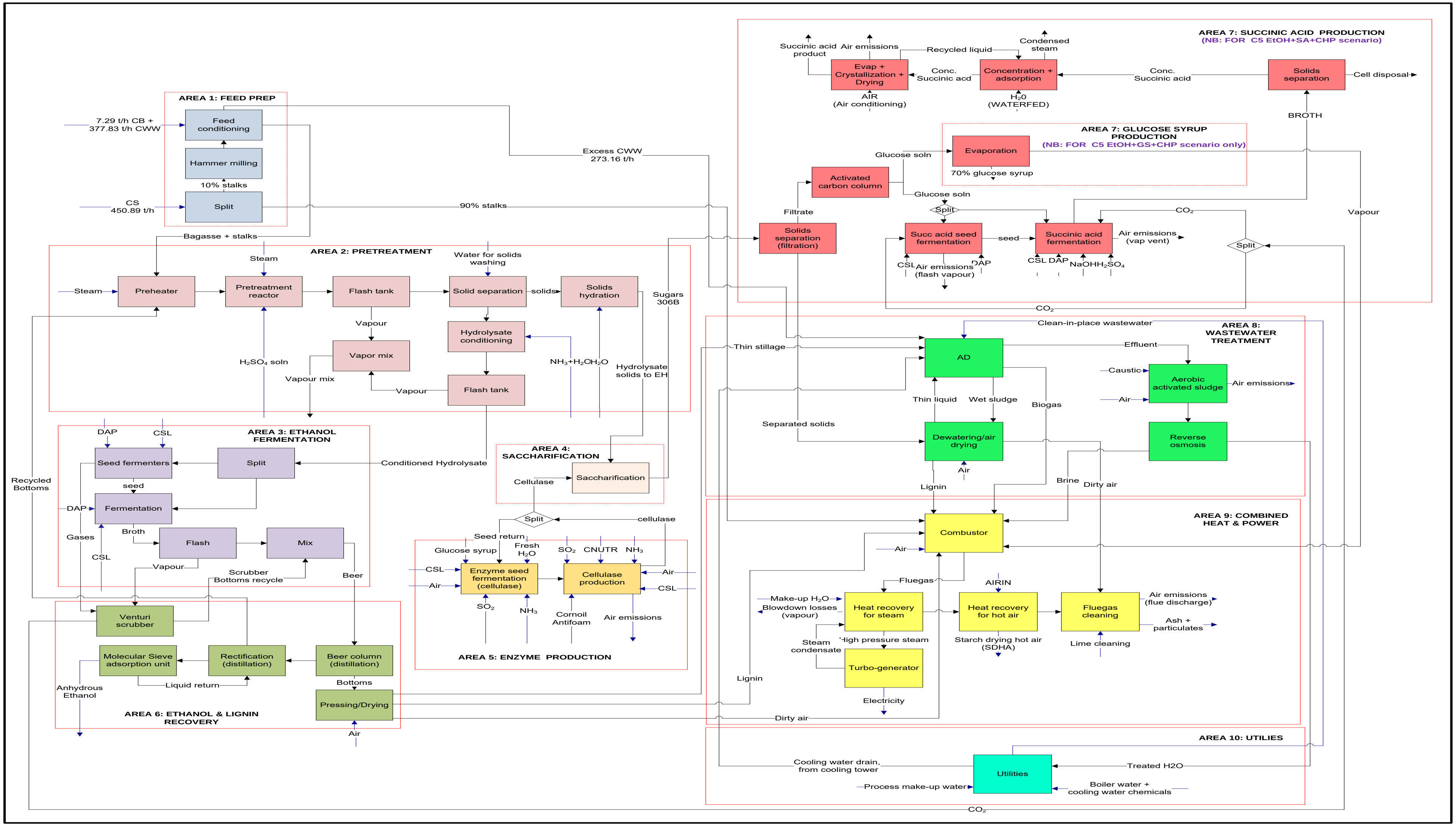


Fig. 7-5: Schematic layout of the cassava starch waste biorefinery co-producing combined heat and power (CHP) from 90% CS and bioethanol plus glucose syrup [scenario (IV)] or succinic acid [scenario (V)] from integrated CWW+CB & 10% CS (Adapted from [298]). In the diagram, AD = anaerobic digestion, CB = cassava bagasse, CNUTR = Cellulase nutrient mix, CS = cassava stalks, CSL = corn steep liquor, CWW = cassava starch wastewater, DAP = diammonium phosphate, EH = enzymatic hydrolysis

7.3 Methodology

The sustainability of the conceptual CWBs is evaluated based on the principles of LCSA, as defined in Eq. 7.1. Thus, the requisite environmental Life Cycle Assessments (eLCA), Life Cycle Costing (LCC), and social Life Cycle Assessments (sLCA) are evaluated based on the principles of Life Cycle Assessments (LCA), Techno-economic Assessments (TEA), and related socio-economic impacts respectively (detailed in section 7.3.3). The eLCA follows the standards defined by the ISO14040 and ISO14044 [155], involving: (i) definition of goal & scope for the study, which includes delineating the system boundary and functional unit (FU) to facilitate comparison of scenarios, (ii) life cycle inventory (LCI), (iii) life cycle impact assessments (LCIA), (iv) results interpretation. The TEA was based on Aspen Plus® process simulations for the CWBs, reported in previous studies [298,300].

$$\text{LCSA} = \text{eLCA} + \text{LCC} + \text{sLCA} \qquad (7.1)$$

Where: eLCA- environmental life cycle assessment; LCC- life cycle costing; sLCA- social life cycle assessment. The additions (+) are figurative and involve methodological valuations (detailed in section 7.3.3.2).

7.3.1 Goal and scope of the study

The main aim of the study is to evaluate and compare the environmental impacts and the sustainability of conceptual CWBs (section 7.2) for purposes of identifying product integration schemes that can support sustainable developments of CWBs. The sustainability of the CWBs was assessed by means of LCSA (Eq. 7.1). The study aims to contribute to knowledge on sustainability of CWBs for stakeholder (CSIs, investors, policy makers, environmentalists) deliberations regarding implementation decisions. In particular, taking into account the environmental and cost constraints to the sustainable developments of CSIs [39,71,72], two stakeholder categories have been considered in the present study: (i) mutual investor-environmentalist perspective, (ii) investor perspective (detailed in section 7.3.3.2). Thus, an investor's priority of investment demands/profitability of the biorefinery, and the environmentalist's priority of environmental savings potential of the biorefineries have been considered in a custom-built Percentage Sustainability Index (PSI) tool for decision-making by the referred stakeholders (detailed in section 7.3.3.2). The presumed geographical setting for the biorefinery is South Africa. The functional unit (FU) is specified as a biorefinery converting 1-ton combined feedstock, comprising (w/w) 45.2% CWW, 0.9% CB, and 53.9% CS (Appendix D, Table D.1). The system boundary is delineated as feedstock transportation, plus biorefinery gate-to-gate, plus landfill treatment of generated ash (Fig. 7-1). The feedstock transportation highlights related environmental burdens incurred by the CWBs, which is absent in the prevailing BAU scenario (section 7.2.1). However, due to the different product options in the CWB scenarios (section 7.2), the specified biorefinery gate boundary poses limitations to the environmentalist decision making concerning comparative environmental savings of the CWBs. Thus, in the PSI design, the eLCA category incorporates the comparative environmental savings prospects via net emissions (net GWP) and net water scarcity (NWS) metrics, relative to the avoided impacts from corresponding fossil products that could be replaced by the bio-products (detailed in sections 7.3.3.1 & 7.3.3.2). The scope definition further assumes the following CWB design:

(i) The CWB is an annex to the host 200 t starch/d CSF, thus, the CWW+CB feedstock is pumped to the CWB (Fig. 7-1).

(ii) The CS feedstock is transported from the farms to the CWB by means of diesel powered trucks (Fig. 7-1).

(iii) Feedstock cultivation is not considered due to the equal feedstock capacities in the CWB and BAU scenarios, thus, of minimal consequence to the comparative sustainability assessments.

(iv) Construction and decommissioning of the biorefinery infrastructure are excluded in the eLCA, due to the negligible environmental contributions to the biorefinery products, attributed to the relatively long lifespans of such infrastructure [301].

7.3.2 Life cycle inventory data and assumptions in assessing the environmental impacts

The LCI background data is obtained from related literature and/or Ecoinvent v.3.5 database [302], detailed as follows:

(i) Data on quantities of raw materials/products, utilities, energy, and emissions for the biorefineries, summarised in the Appendix D (Table D.1), is obtained from Aspen Plus® simulated mass and energy balances in previous works [298,300].

(ii) In the BAU scenario, where the ash from stalk burning is left untreated on the land (section 7.2.1), ash composition reports for thick CS by Veiga et al. [175] is adopted.

(iii) In the CWB scenarios, relative to the landfill treatment of generated ash (Fig. 7-1), due to similarity of wood ash compositions to CS ash [175], Ecoinvent v.3.5 LCI data for wood ash landfill treatment is assumed [302].

(iv) Concerning the CS feedstock, 20% w/w of the generated stalks is used for planting and social uses such as heating fuel [82,303], thus, only 80% is recoverable for conversion in the CWB. In addition, the CS production rate is based on yield reports of CS-to-cassava root ratio of 0.51 [82]. The CS transportation distance, from farms to the CWB, is estimated relative to reports of 48 km [72] radius for the primary sustainable CS (0.8 x 0.51 x 842 t cassava/d; 343.54 t CS/d) associated with the 842 t cassava/d feedstock for the 200 t/d CSF (Fig. 7-1). Consequently, the total CS (~10821 t/d) transportation distance is proportionally estimated at ~270 km radius. Hence, Ecoinvent v.3.5 LCI data [302] for diesel truck for short haul distance (<322 km) have been considered.

(v) For CWW+CB transportation from the CSF to the annex biorefineries, pumping to 2.47 atm with a pump power of 32.77 kW (Aspen Plus® prediction), supplied using the generated bioelectricity (Fig. 7-1) in the CWBs or coal based grid power in the BAU [298,300], is presumed.

(vi) Coal based grid power is assumed for supplying the total electricity demands for the AD biogas SDHA process in the BAU scenario [300], which was predicted at 360 kW through Aspen Plus® simulations [300].

In eLCA for multi-product systems such as biorefineries, standardized methodologies are required to assess the environmental impacts of the wide-ranging products, where system expansion or partitioning are well established methods [155,304]. System expansion involves redefining the FU to include functions of all co-products, or allocations of avoided impacts from products assumed to be substituted by the co-products to the selected main product. Conversely, the partitioning method considers allocation of burdens to all products, based on physical (mass, volume, or energy content) or economic (production cost, market value) attributes. Partitioning by economic allocation using total revenues (detailed in Appendix D, Table D.2), which is an essential attribute to the study's interest of biorefinery sustainability [199,305], is considered in the present study.

7.3.3 Sustainability assessments of the cassava wastes biorefineries

7.3.3.1 Sustainability metrics

In view of the concerns on water & land pollution, and the high carbon footprints associated with current CSF waste management schemes (section 7.1), the environmental metrics deemed relevant for consideration include global warming potential (GWP), freshwater eutrophication potential (FEP), freshwater ecotoxicity potential (FETP), terrestrial acidification potential (TAP), terrestrial ecotoxicity potential (TETP), and fossil resource scarcity potential (FRSP).

The proposed methodology for the LCSA involves evaluation of the environmental metric as the conventional environmental life cycle assessment (eLCA), the costs metric (called Life Cycle Costing- LCC) as costs implications for each stage of the life cycle, and the social metric (called Social Life Cycle Assessment- sLCA) as the socio-economic impacts such as job creation among others [67], as summarized in Eq. 7.1. The referred metrics consist of sub-metrics that could be classified into two categories: 'hard' and 'soft' criteria [306]. The hard criteria refer to quantifiable factors that can be evaluated and expressed in crisp values (e.g. capital costs), whereas the soft criteria are qualitative or subjective factors evaluated based on knowledge or experience of the decision-maker or stakeholder (e.g. social acceptability of a product) [306]. In the present study, because of the lack of empirical stakeholder experiences due to the hypothetical status of the CWBs and unexplored in-depth stakeholder engagements, the proposed preliminary sustainability framework was confined to the hard criteria summarized in Fig. 7.6.

The eLCA was achieved using the related ReCiPe 2016 midpoint (H) v1.03 method [307] via simulations in SimaPro 9.0.0.49 software [186]. Characterization results were chosen for the referred environmental impact categories to enable various stakeholders to subject the findings to contextually relevant factors. Furthermore, to facilitate the incorporation of holistic environmental benefits of the CWBs vs. corresponding fossil-based processes in the LCSA, mainly to meet the environmentalist stakeholder's priority of comparative environmental benefits of the CWBs (detailed in section 7.3.3.2), in addition to the FEP, FETP, TAP, TETP and FRSP, net global warming potential (Net GWP) and net water scarcity (NWS) indicators have been included in the eLCA (Fig. 7.6) The Net GWP refers to the total biorefinery GWP minus the total GWP for equivalent fossil-based products (processes), detailed in the Appendix D (Table D.3). The NWS is similar to the Net GWP, except that the metric of interest is the water resource scarcity (Appendix D, Table D.3). The respective Net GWP and NWS were evaluated based on the single issue GWP method of IPCC 2013 (GWP_{100a}) and the water footprint method of Hoekstra et al. [302,308].

In relation to the LCC, relative to the investment and profitability priorities of the targeted investor stakeholder, the Net Present Value (NPV) profitability indicator, total production costs (TPC), and total capital investments (TCI) have been considered [296]. The NPVs were estimated relative to year 2018 economic context for South Africa. The estimations involved projection of the TPC, TCI, and total revenues from product sales, which were based on simulated mass and energy balances in Aspen Plus®, detailed in previous works [298,300]. The referred estimates, together with assumed operational and economic factors, including debt financing (debt-to-equity ratio of 1.5; 8% interest rate & 10-year recovery), operating period of 8410 h/a & plant life of 30 years, real term discount rate of 9.7% & inflation rate of 5.7%, were used to project discount cash flows, which were used to evaluate the NPVs as elaborated in the previous works [298,300].

With respect to the sLCA, the job creation metric has been considered [295,296], and was estimated as the skilled + unskilled labour projections for the biorefinery facility, based on the previous studies [298,300]. High costs and unreliable supplies of energy have been cited as constraints to industrial developments of cassava in most of the deprived cultivation regions, such as Thailand [73], Ghana [23] and Nigeria [12]. Energy security benefits from the CWBs could, therefore, enhance industrial expansions and related socio-economic developments, thus, considered in the social criteria [295,306]. The prospective contribution of the CWBs to energy security was estimated as the net surplus electricity after meeting the in-house requirements (see Fig. 7-1 & Appendix D, Table D.1). Due to the human health risks concerns for biorefineries [150], human toxicity potential (HTP) was also included in the sLCA [293], and was evaluated using the SimaPro models for the CWBs and the methodology of CML-IA baseline v3.05 [296].

7.3.3.2 Sustainability indicator estimations

For purposes of comparing the TBL sustainability of alternate projects, several approaches to integrating the procedure or results for the various metrics of the LCSA (eLCA, LCC, sLCA) into a sustainability index, including weighting and normalization of the data, have been proposed [64,66]. In the conventional weighting approach, the weights are based on the importance of the metrics and the priorities of the stakeholders (e.g. investors, policy makers, employees) [293], resulting in potential drawbacks of introducing uncertainties in the outcomes. As a result, the integration of the metrics into a single sustainability index has been recommended as an optional step in LCSA that could be tailored for context-specific purposes in tune with the project's objectives [67]. Therefore, the reliability of the sustainability index depends on the estimated weights, with the objective method (e.g. entropy weighting) and subjective method (e.g. analytic hierarchy process- AHP) of estimations identified as useful with regards to accounting for importance/effects of each metric and preference of the decision-makers respectively [309]. In effect, reliable weight estimates will require direct stakeholder participation and inputs via group discussions or surveys [293,294].

In relation to the proposed CWBs, because of the unexplored stakeholder engagements, a tailored approach was developed for the integration of the LCSA metrics into a percentage sustainability index (PSI) (summarized in Fig. 7.6), which was based on reports of high environmental burdens & waste treatment costs in CSFs [39,71,72], as well as potential high investment costs constraint to the uptake of the CWBs [1]. Hence, two perspectives of investment decision-making have been considered in the PSI weightings: (i) Mutual investor-environmentalist viewpoint: high and equal LCC & eLCA (40:40%) with low sLCA (20%) [**Case A baseline**], (ii) Investor viewpoint: high LCC (50%) with equal eLCA & sLCA

[1] Observations from field visits and personal discussions with managements of Ayensu Starch Company Limited (cassava starch facility) and Caltech Industries (cassava ethanol facility) in the Central region (Awutu-Bawjiase) and Volta region (Hodzo) of Ghana, respectively.

(25:25%) [**Case B baseline**]. In addition, for both Cases A & B, sensitivity analysis was performed to analyze the responses of the sustainability (PSI) to changes in the total weights of the LCC and eLCA, which involve ±5% adjustments of the LCC or eLCA weights for ranges from 0% to their summed weight (i.e. A- 80%, B- 75%), while keeping the sLCA's constant. The sub-weightings prioritized motivations of profitability [allocation of 80% of LCC to NPV & 10% each to TCI and TPC] and environmental savings [allocation of 50% of eLCA to the environmental savings (Net GWP & NWS) & 50% to the biorefinery gate impacts], as illustrated for the Case A in Table 7.2. For instance, it is likely that irrespective of the capital (TCI) and production cost (TPC) demands, profitable investment returns (positive NPV) could motivate uptake of the CWBs. Relevant to the sLCA, the need to consider the impacts on the socio-economic wellbeing of all actors along the value chain (i.e. from raw material producers to products consumers) has been emphasized [294]. The related limitations in the sLCA metrics were factored in their sub-weightings (allocations of 20% of sLCA to job creation, 30% to energy security & 50% to HTP). For example, the job creation estimate reflects employment in only the CWB facilities (section 7.3.3.1), whereas the HTP and the energy security may reflect impacts on broader actors (e.g. HTP includes impacts from raw materials & end-products; the surplus electricity exports could facilitate external industrial expansions). The weighted metrics were internally normalized among the CWB scenarios. Thus, for parameters with minimum targets (e.g. human toxicity potential) and maximum targets (e.g. NPV), the weighted metrics were normalized against the lowest and highest values respectively (see Table 7.2). The internally normalized results for each CWB scenario are then added to obtain the CWB's PSI (see Table 7.2).

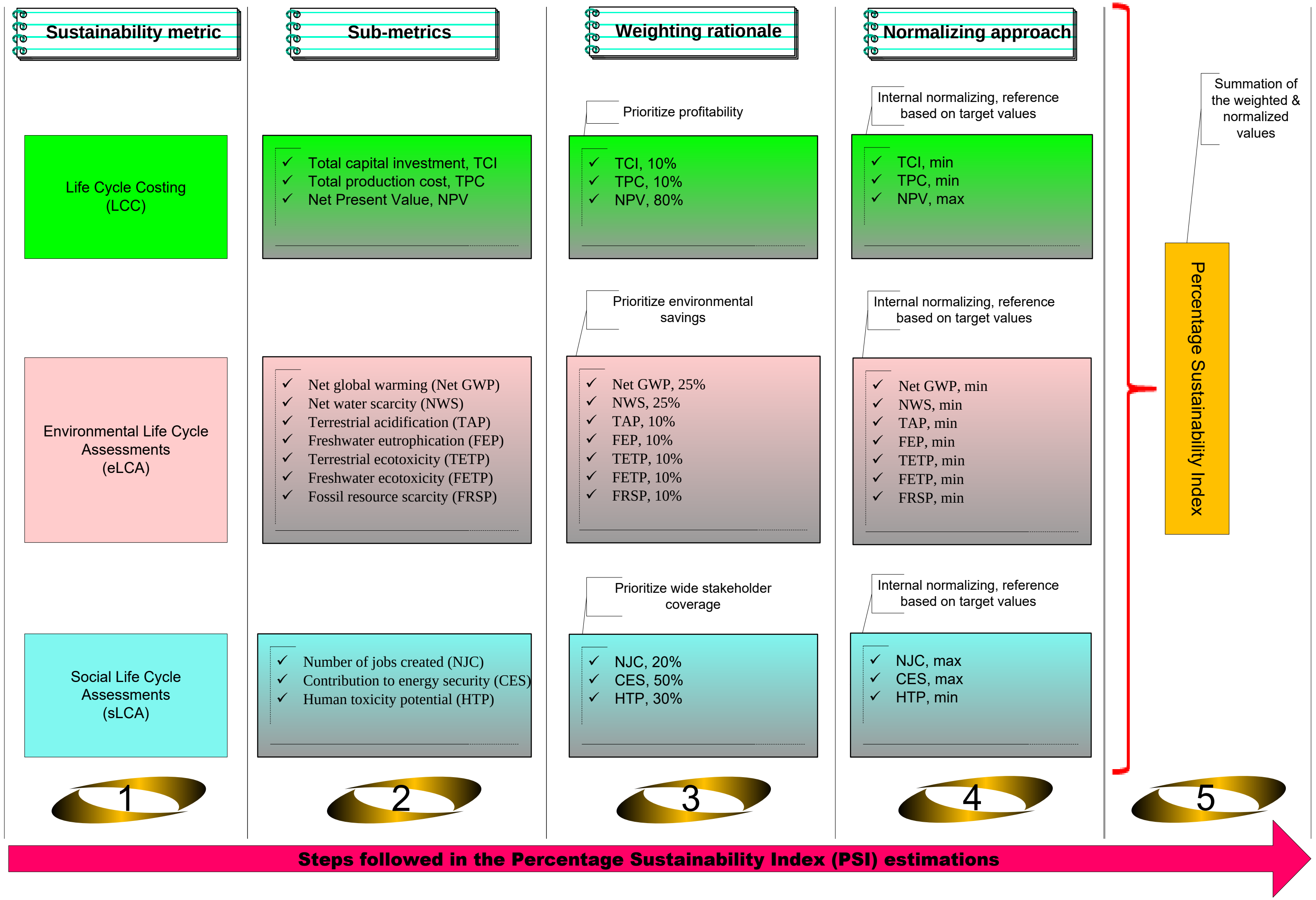


Fig. 7-6: The percentage sustainability index (PSI) framework applied in this study. Net GWP = total biorefinery GWP minus total GWP for the equivalent fossil-based products (processes) & NWS = total biorefinery water scarcity minus total water scarcity for the equivalent fossil-based products/processes (see section 7.3.3.1 & Appendix D, Table D.3)

Table 7.2: Summary of the life cycle sustainability assessment (LCSA) metrics and illustration of the sustainability index calculations for the biorefineries

	Targeted value	BAU Scenario	CHP, scenario (I)	C6EtOH+CHP, scenario (II)	C5-C6EtOH+CHP, scenario (III)	C5EtOH+GS+CHP, scenario (IV)	C5EtOH+SA+CHP, scenario (V)	
Life cycle costing (LCC) [a]								
Total capital investment, TCI (million US$)	Minimum	51.87	545.11	594.96	921.918	951.204	1007.61	
Total production cost, TPC (million US$/a)	Minimum	8.87	285.28	289.84	280.75	290.81	331.16	
Net Present Value, NPV (million US$)	Maximum	92.71	438.53	331.03	-1001.95	-388.53	3.21	
Environmental life cycle (eLCA) [b]								
Net GWP (kg CO_2) [c]	Minimum (negative values preferable)	1.3	-379	-356	-146	-211	-182	
Net water scarcity (NWS) (m^3) [c]	Minimum (negative values preferable)	-0.0042	2.06	1.42	2.65	2.07	4.49	
Terrestrial acidification (kg SO_2)	Minimum	0.55	0.32	0.31	0.39	0.39	3.60	
Freshwater eutrophication (kg P eq)	Minimum	0.90	0.02	0.02	0.02	0.02	0.06	
Terrestrial ecotoxicity (kg 1,4-DCB)	Minimum	6.63	19.05	19.10	27.92	28.40	68.90	
Freshwater ecotoxicity (kg 1,4-DCB)	Minimum	0.19	70.42	70.04	64.74	64.76	122.25	
Fossil resource scarcity (kg oil eq)	Minimum	0.57	7.22	7.27	8.89	9.20	22.39	
Social life cycle (sLCA)								
Job creation (number of jobs created) [d]	Maximum	23	32	46	60	65	69	
Energy security (net electricity export, kW)	Maximum	0.00	362.52	345.93	147.59	199.12	195.67	
Human toxicity potential (kg 1,4-DB eq)	Minimum	9.54	19.74	20.73	19.93	20.19	46.30	
Percentage sustainability index (PSI) for the 'Case A' sustainability perspective								**Weighting factors (%)**
Total capital investment, TCI		4.00	0.38	0.35	0.23	0.22	0.21	4
Total production cost, TPC		4.00	0.12	0.12	0.13	0.12	0.11	4
Net Present Value, NPV		6.77	32.00	24.16	-73.11	-28.35	0.23	32
Total LCC sustainability index (%)		**14.77**	**32.50**	**24.63**	**-72.76**	**-28.01**	**0.55**	**40.00**
Net GWP		-0.03	10.00	9.39	3.85	5.57	4.80	10.00
Net water scarcity (NWS)		10.00	-0.020	-0.029	-0.016	-0.020	-0.009	10.00
Terrestrial acidification		2.29	3.87	4.00	3.23	3.20	0.35	4.00
Freshwater eutrophication		0.11	3.93	3.96	4.00	3.92	1.52	4.00
Terrestrial ecotoxicity		4.00	1.39	1.39	0.95	0.93	0.38	4.00
Freshwater ecotoxicity		4.00	0.0106	0.0107	0.0115	0.0115	0.0061	4.00
Fossil resource scarcity		4.00	0.31	0.31	0.25	0.25	0.10	4.00
Total eLCA sustainability index (%)		**24.36**	**19.50**	**19.03**	**12.29**	**13.86**	**7.15**	**40.00**
Job creation (number of jobs created)		1.33	1.86	2.67	3.48	3.77	4.00	4
Energy security (net electricity export)		0.00	6.00	5.73	2.44	3.30	3.24	6
Human toxicity potential		10.00	4.83	4.60	4.79	4.72	2.06	10
Total sLCA sustainability index (%)		**11.34**	**12.69**	**12.99**	**10.71**	**11.79**	**9.30**	**20.00**
Total sustainability index (%)		**50.47**	**64.70**	**56.65**	**-49.77**	**-2.36**	**17.00**	**100.00**

[a] Values adopted from previous works- BAU values from [300] & scenarios (I)-(V)'s from [298]; [b] Simulation results in the present study for 1-functional unit (processing of 1-ton collective feedstock, comprising (w/w) 45.2% CWW + 0.9% CB + 53.9% CS); [c] Net GWP = total biorefinery GWP minus total GWP for the equivalent fossil-based products (processes) & NWS = total biorefinery water scarcity minus total water scarcity for the equivalent fossil-based products (processes) (see section 7.3.3.1& Appendix D, Table D.3). Therefore, negative Net GWP & NWS results imply environmental savings by the CWB products vs. corresponding fossil-products; [d] Skilled + unskilled labour projections for the biorefineries based on the previous studies [298,300]. 'Case A' sustainability perspective (mutual investor-environmentalist viewpoint, see section 7.3.3.2). BAU = business-as-usual, C5EtOH = pentose based bioethanol, C5-C6EtOH = pentose + hexose based bioethanol, C6EtOH = hexose based bioethanol, CB = cassava bagasse, CWW, cassava starch wastewater, CS, cassava stalks, CHP = combined heat and power, GS = glucose syrup, GWP, global warming potential, SA = succinic acid.

7.3.3.3 Sensitivity analysis of the sub-metric weighting impacts on the sustainability projections

To establish the impacts of the sub-weightings on the PSIs, a related sensitivity analysis was performed using the 'Case A' stakeholder perspective (section 7.3.3.2) as case study. The analysis involved comparing the PSI for the 'Case A' baseline weighting scenario (presented in Table 7.2) to PSI values corresponding to various scenarios of adjusted sub-weights for each sub-metric: (i) Scenario 1 (Sc. 1)- Equal sub-weights for each category of the LCSA metrics (i.e. 13.33% each for TCI, TPC & NPV; 5.714% each for Net GWP, NWS, TAP, FEP, TETP, FETP & FRSP; 6.66% each for job creation, energy security & human toxicity potentials) (see Appendix D, Table D.4), (ii) Scenarios 2-14 (Sc. 2-14)- For each category (i.e. LCC, eLCA, or sLCA), 35% of the total category weight is assigned to a sub-metric (dominant metric) while the 65% is equally split among the other sub-metrics [i.e. $\hat{W}_j = 35\%\ T$, ($j = 1, 2, 3\ldots$); $\hat{W}_k = 65\%\ T/(n-1)$, ($k = 1, 2, 3\ldots$); where $j \neq k$, $\hat{W}_{j\ \mathrm{or}\ k}$ = weight of the sub-metric 'j' or 'k', T = total category weights, n = total number of sub-metrics in the category]. This weighting process is repeated in a successive manner for the subsequent sub-metrics in the category (subsequent scenarios), while maintaining equal sub-weightings for the other categories (detailed in Appendix D, Table D.4).

7.4 Results and discussions

7.4.1 Environmental impact potentials of the biorefineries

7.4.1.1 Global warming potential (GWP) and fossil resource scarcity potential (FRSP)

In the simulated CWBs, transportation of CS from farms to the CWBs contribute substantially (23-68%) to the GWP (Fig. 7.7a), thus, a possible hotspot for mitigation deliberations. The estimated CS transportation distance of 270 km radius was based on avg. CS-cassava root yield ratio of 0.51 [82] (section 7.3.2). Reports of higher CS-to-cassava yields, up-to 0.85 [82], implies existing possibilities for cultivation of higher CS cultivars, which could potentially reduce the transportation distance, thus an avenue to substantial reductions in the

GWPs of the biorefineries. Transportation of CS from farms to CWBs, using diesel powered trucks, contributed substantially to the GWP profiles, at respective contributions of ~68, 52, 50, 49, and 23% for the scenarios (I)-(V) (Fig. 7.7a), hence, a prospective avenue for GWP reductions in the CWBs.

With respect to the BAU scenario, the GWP of 4.50 kg CO_2 eq/FU (Fig. 7.7a) is mainly due to the non-renewable coal-based grid power presumed for supplying the AD biogas-SDHA process power (360 kW) [300] and the FGD lime, with contributions of 9.4% and 88.7% (respectively) of the GWP (Fig. 7.7a). This assertion is further supported by the comparable avg. GWP reports of 0.84 kg CO_2 eq/kWh for pulverised coal power systems (without carbon capture and storage) [310], relative to the GWP of ~0.45 kg CO_2 eq/kWh coal power consumed for the BAU scenario [Calculated as: (0.094 x 4.5 kg $CO_{2\ eq}$/t feedstock) x (385.12 t feedstock/h) x (1/360 kW)].

The GWP associated with electricity production seemingly doubles (7.7 vs. 14.2 kg CO_2 eq/FU) when C6 bioethanol is integrated into the CHP (scenario II) (Fig. 7.7a). Considering the relatively similar net power capacities for the referred scenarios (~363 vs. 346 kWh/FU; Table A.1), the large differences in the electricity GWP could be a reflection of the relatively high economic allocation factor (~25-folds higher) for electricity vs. that of bioethanol (Table A.2), attributed to the high total revenue for scenario (II) electricity (~US$ 312 million) compared to bioethanol's (~US$12 million) (Table A.2).

Comparing scenario (III) to (IV) revealed that the diversion of the C6 sugars for glucose syrup conversion barely increased the GWP (increased by 3.7%) (Fig. 7.7a). This could be explained by the similar amounts of chemicals, enzymes, nutrients and non-renewable inputs to both scenarios [150], with the minor differences occurring in the ethanol fermentation and CHP operations, such as fermentation chemicals (CSL, DAP) and boiler/cooling tower chemicals (Fig. 7.7a; Appendix D, Table D.1). Conversely, the conversion of the diverted C6 sugars to SA, which was modelled in scenario (V) (Fig. 7-5), increased the GWP by 121% when compared to scenario (III) (Fig. 7.7a). As shown in the breakdown of the GWP for scenario (V) (Fig. 7.7a), the SA production section accounted for approx. 64% of the GWP, which is largely due to the high volumes of non-biogenic chemical consumptions, particularly H_2SO_4 (29.44 kg/FU) and NaOH (24.61 kg/FU) in SA fermentation and recovery (Fig. 7.7a; Appendix D, Table D.1) [311].

In general, the GWP increased with the number of products (Fig. 7.7a). Interestingly, for all the CWBs, the trend of FRSP was similar to the GWP's (Fig. 7.7a vs. b), which is corroborated by similar findings for sugarcane biorefineries [199,295]. The similar FRSP trends support assertions that the GWPs are largely due to the fossil based inputs, while for FRSP, the extent of fossil based inputs corresponds with the number of products (Fig. 7.7b).

7.4.1.2 Freshwater eutrophication potential (FEP)

FEP refers to excessive nutrient enrichment of freshwater ecosystems with resultant increase in growth of aquatic plants or algae that reduces water quality [312]. Relative to the studied CWBs, nitrogen (N) and phosphorous (P) are the major potential eutrophication nutrients, which could originate from operations such as volatilization of nitrogen based inputs (e.g. NH_3 & DAP in the cellulase enzyme production, and ethanol/SA fermentations), emission of NO_x from combustion units, and release of phosphates from biofuel combustion and ash treatments at landfills [310,313].

The CWBs demonstrate potential for substantial reductions in the FEP relative to the base case BAU scenario. The BAU's FEP (0.9 kg P eq) was shown to be 36.92, 37.16, 37.54, 36.79, and 14.25-folds higher than scenarios (I)-(V) respectively (Fig. 7.7c). From the BAU FEP breakdown (Fig. 7.7c), open burning of CS accounted for 97% (Fig. 7.7c), which may be justified by the high air and land emissions due to the absence of treatment of the flue gas and ash (Fig. 7-2a) [310]. Furthermore, taking into account the 85% COD removal presumed in the

AD simulation [300], the minimal contribution of the AD biogas-SDHA process to the BAU's FEP (3%, Fig. 7.7c) could be explained by the relatively low nutrient content of the AD digestate disposed into waterbodies (Fig. 7-2a).

The extra nutrient emissions in scenario (I), due to the additional power capacity (Appendix D, Table D.1), is equivalent to the nutrient emissions associated with the integrated GS and/or bioethanol in scenarios (II), (III) or (IV), but ~62% lower than the integrated SA's in scenario (V). From the FEP results (Fig. 7.7c), equal performances (~0.024 kg P eq) were shown for scenarios (I)-(IV), which increased to 0.063 kg P eq in scenario (V).

Hence, for the BAU, CS burning represents hotspot for FEP, despite there being no value derived from the burning. Therefore, considering the substantial reductions in the FEP for CWBs vs. the BAU (Fig. 7.7c), the suggested integration of the CS (farm wastes) with the CSF's wastes (CWW+CB) for biorefinery exploits could be a beneficial strategy for value-addition to waste resources while safeguarding against water resource contaminations.

7.4.1.3 Freshwater ecotoxicity potential (FETP), terrestrial ecotoxicity potential (TETP), and terrestrial acidification potential (TAP)

FETP and TETP relate to the environmental impacts of released toxic materials on freshwater or terrestrial ecosystems respectively, whereas TAP measures the impacts of acidifying pollutants released on land [310,314]. Thus, in addition to the FEP emissions in the CWBs (section 7.4.1.2), SO_x emissions from the fuel combustions, life cycle of H_2SO_4 (pre-treatment/SA fermentation) [301], volatilization of Na_2SO_4 salts (SA fermentation), metals in combustion flue gas or boiler ash, $CaSO_4$ salts from FGD (Fig. 7-2-Fig. 7-4), toxic or acidic compounds such as cyanide & propionic acids in the AD digestate (Appendix D, Table D.1), which invariably end up in water bodies or land, contribute to the FETP and TETP/TAP respectively [313,315,316].

Comparable FETPs, TETPs and TAPs were shown for scenarios (I) vs. (II) and (III) vs. (IV), attributable to the minimal differences in the chemical demands (Appendix D, Table D.1), as well as the similar approaches to handling process wastes or emissions (Fig. 7-2-Fig. 7-4). The FETP for the BAU, projected at 0.187 kg 1,4-dichlorobutane (DCB) (Fig. 7.7d), was considerably low compared to the CWBs' values at ~70 kg 1,4-DCB for the (I)-(II), ~64.8 kg 1,4-DCB for (III)-(IV), and ~122 kg 1,4-DCB for (V) (Fig. 7.7d). In relation to the TETP, compared to the BAU, higher values were shown for the CWBs, which were comparable for scenario (I) vs. (II) and (III) vs. (IV) (Fig. 7.7e). For the TETP, the BAU's TETP (6.63 kg 1,4-DCB) mainly emerged from the AD biogas-SDHA process (99.7%), with only 0.3% contribution from the open burning of CS (Fig. 7.7e). In contrast to the FETP and TETP trends, the BAU's TAP (0.547 kg SO_2 eq) was 1.7-folds that of (I)-(II) and 1.4-folds that of scenarios (III)-(IV) (Fig. 7.7f).

The proposed strategy for GWP mitigations, comprising reduction in transportation distance via cultivation of high CS cultivars (section 7.4.1.1), could equally minimise the TAPs of the biorefineries. Relevant to the TAP, the substantial contributions from CS transportation, particularly for scenarios (I)-(II) (~35%) and (III)-(IV) (~29%) (Fig. 7.7f), is imperative to policy designs for TAP mitigations.

7.4.1.4 Comparing the environmental impacts for the bioethanol production sections

As implied in section 7.1, biorefinery processes based on edible crops (e.g. cassava) and non-food crops or residues as feedstock (e.g. switch grass, CS) can be classified as first generation (1G) and second generation (2G) biorefineries respectively [317]. The 1G is a well-developed technology with widespread commercial applications, such as the sugarcane molasses-based ethanol industry in Brazil [318]. Conversely, 2G biorefineries are generally in development stages [49]. The 2G has received considerations over 1G regarding food security impacts [80]. However, the environmental performances for 1G vs. 2G processes are inconsistent, attributable to the diversity in conversion technologies for both processes [297,317]. For instance, 1G sugarcane molasses-based ethanol process consists of acid hydrolysis, yeast fermentation & ethanol recovery [61], whereas 2G sugarcane bagasse & trash-based bioethanol consists of pre-treatment/EH, fermentation & ethanol recovery [319].

Therefore, to analyze the environmental potentials of the proposed CWBs vs. the established 1G industries, the environmental impacts of the 2G bioethanol production from the CWBs [i.e. scenarios (II)-(V)] have been compared to the commercial ethanol from molasses fermentation (1G ethanol) in sugarcane biorefineries in Brazil (Fig. 7-8a) [302]. It was shown that 1G ethanol presents the lowest impacts for FRSP, FEP, FETP & TAP, and vice versa for GWP & TETP (Fig. 7-8a). Thus, compared to the CWB bioethanol, ethanol from the 1G molasses process is more sustainable for most impacts. However, the potential benefits of substantial reductions in TETP and GWP by the CWB bioethanol is imperative for considerations in mitigating climate change impacts of fossil transport fuels. Amongst the studied CWBs, inconsistent trends were shown for the environmental categories, with comparative differences ranging ~90% for the TAP and ~32-50% for all other categories (Fig. 7-8a). Hence, with the exception of the TAP, the predicted impacts for the bioethanol from the CWBs are fairly comparable (Fig. 7-8a). Variations in the process approach and economic allocation factors (Table A.2) can be cited for the observed differences. For instance, while 1% H_2SO_4 pre-treatment and subsequent NH_3 conditioning of the starch wastes precedes enzymatic hydrolysis in the C5-C6EtOH process (III) (section 6.2.1.3.3), only enzymatic hydrolysis was employed in the C6EtOH process (II) (section 6.2.1.3.2).

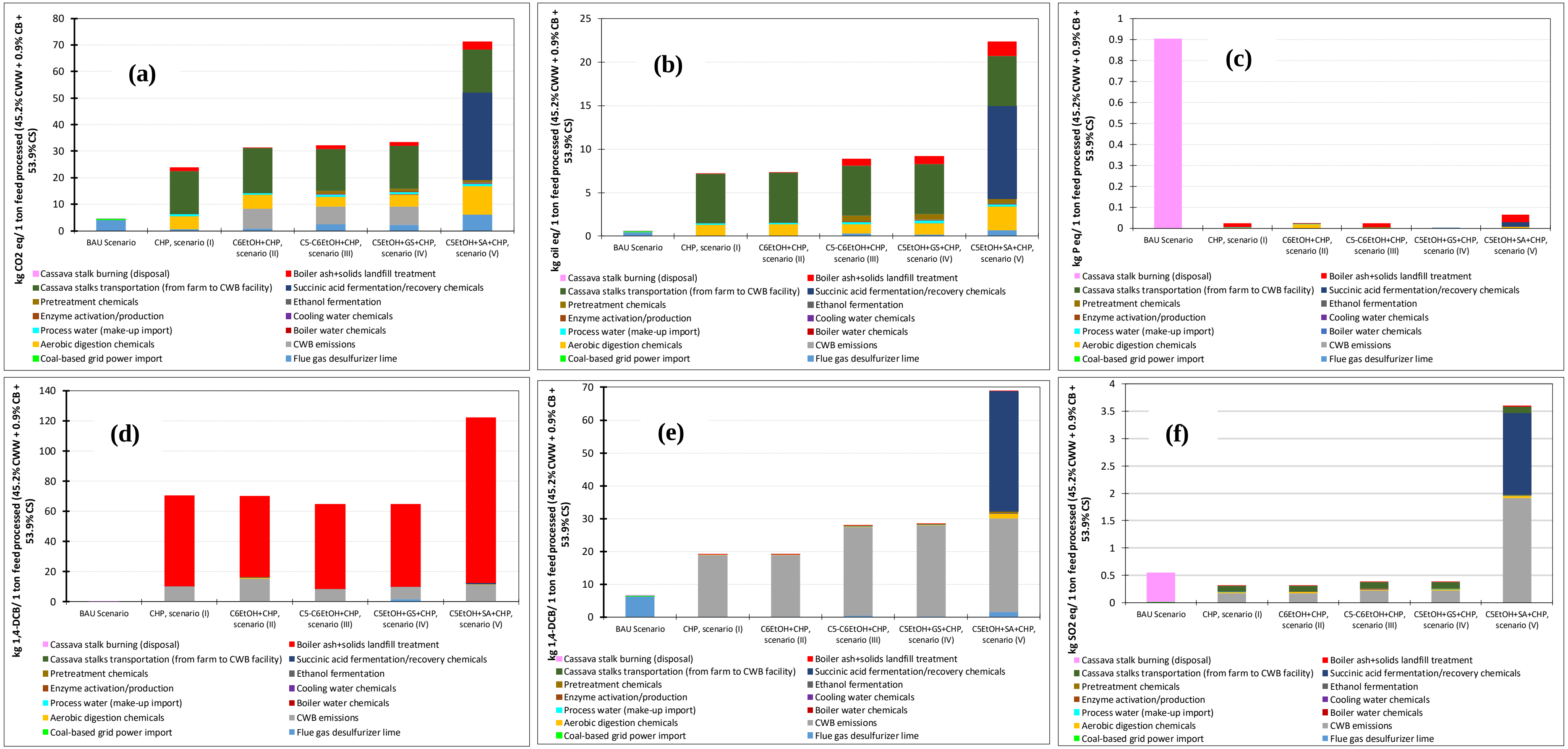
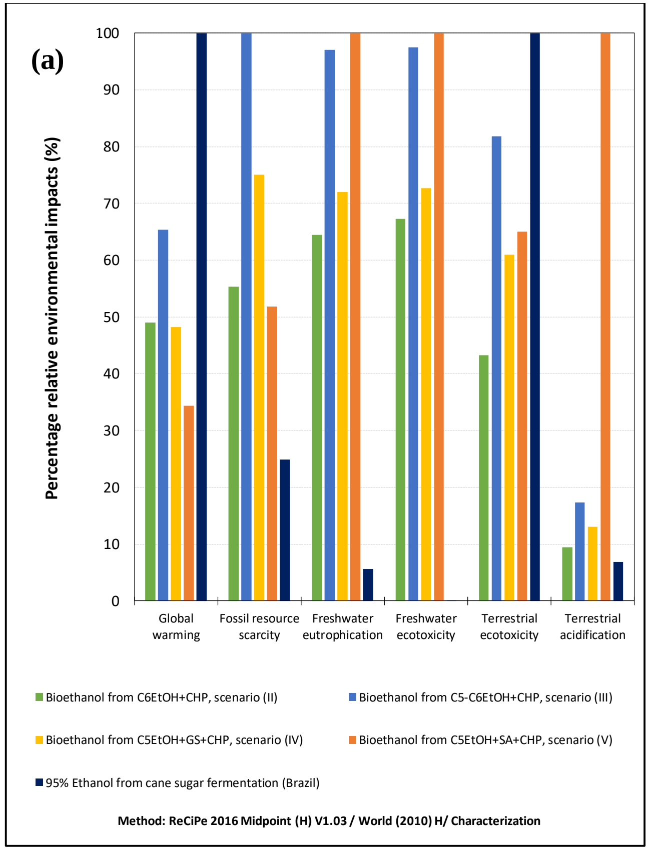
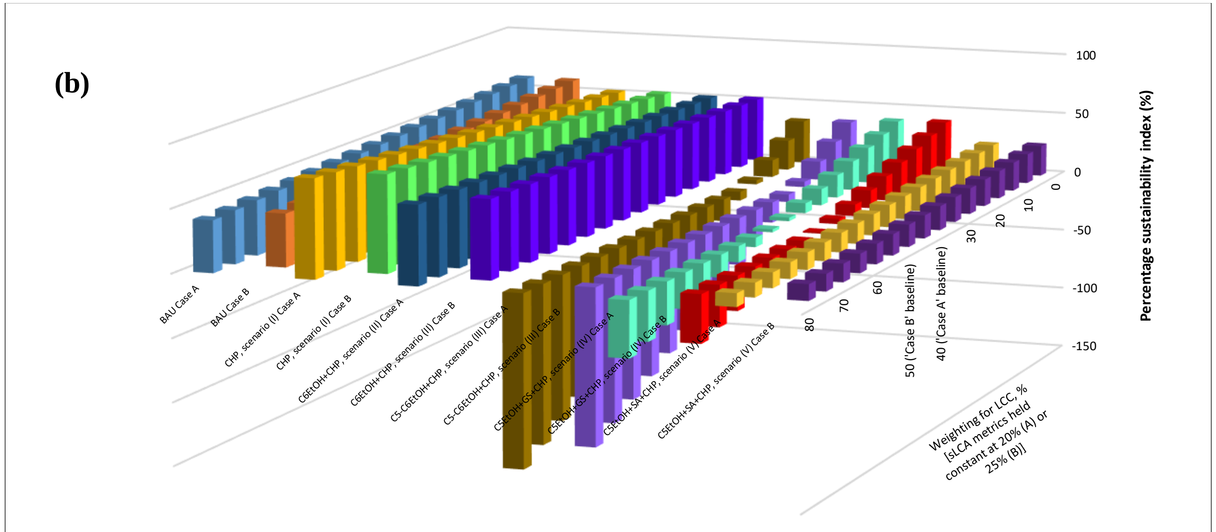


Fig. 7-7: Results of the Life Cycle Assessments for the cassava wastes biorefineries, based on the method of ReCiPe 2016 midpoint (H) v1.03/ World (2010) H/ Characterization. (a) Global warming, (b) Fossil resource scarcity, (c) Freshwater eutrophication, (d) Freshwater ecotoxicity, (e) Terrestrial ecotoxicity, (f) Terrestrial acidification. In the Figure, BAU = business-as-usual, C5EtOH = pentose based bioethanol, C5-C6EtOH = pentose + hexose based bioethanol, C6EtOH = hexose based bioethanol, CHP = combined heat and power, CWB = cassava wastes biorefinery, GS = glucose syrup, SA = succinic acid.





	0	5	10	15	20	25	30	35	40 ('Case A' baseline)	45	50 ('Case B' baseline)	55	60	65	70	75	80
BAU Case A	60.07	58.87	57.67	56.47	55.27	54.07	52.87	51.67	50.47	49.27	48.07	46.87	45.67	44.47	43.27	42.07	40.87
BAU Case B	59.85	58.65	57.45	56.25	55.05	53.85	52.65	51.45	50.25	49.05	47.85	46.66	45.46	44.26	43.06	41.86	
CHP, scenario (I) Case A	51.70	53.32	54.95	56.57	58.20	59.82	61.45	63.07	64.70	66.32	67.95	69.57	71.20	72.82	74.45	76.07	77.70
CHP, scenario (I) Case B	52.43	54.05	55.68	57.30	58.93	60.56	62.18	63.81	65.43	67.06	68.68	70.31	71.93	73.56	75.18	76.81	
C6EtOH+CHP, scenario (II) Case A	51.06	51.76	52.46	53.16	53.86	54.56	55.26	55.95	56.65	57.35	58.05	58.75	59.45	60.15	60.85	61.55	62.25
C6EtOH+CHP, scenario (II) Case B	51.93	52.63	53.33	54.03	54.73	55.43	56.12	56.82	57.52	58.22	58.92	59.62	60.32	61.02	61.72	62.42	
C5-C6EtOH+CHP, scenario (III) Case A	35.28	24.65	14.02	3.39	-7.24	-17.87	-28.51	-39.14	-49.77	-60.40	-71.03	-81.66	-92.29	-102.92	-113.55	-124.19	-134.82
C5-C6EtOH+CHP, scenario (III) Case B	36.42	25.79	15.16	4.53	-6.10	-16.73	-27.36	-38.00	-48.63	-59.26	-69.89	-80.52	-91.15	-101.78	-112.41	-123.04	
C5EtOH+GS+CHP, scenario (IV) Case A	39.51	34.27	29.04	23.81	18.57	13.34	8.10	2.87	-2.36	-7.60	-12.83	-18.07	-23.30	-28.53	-33.77	-39.00	-44.23
C5EtOH+GS+CHP, scenario (IV) Case B	40.72	35.49	30.25	25.02	19.79	14.55	9.32	4.09	-1.15	-6.38	-11.62	-16.85	-22.08	-27.32	-32.55	-37.79	
C5EtOH+SA+CHP, scenario (V) Case A	23.60	22.78	21.95	21.12	20.30	19.47	18.65	17.82	17.00	16.17	15.35	14.52	13.70	12.87	12.04	11.22	10.39
C5EtOH+SA+CHP, scenario (V) Case B	25.03	24.21	23.38	22.56	21.73	20.90	20.08	19.25	18.43	17.60	16.78	15.95	15.13	14.30	13.48	12.65	

Fig. 7-8: (a) Relative environmental impacts for 1-ton bioethanol production in the cassava waste biorefineries [i.e. only the scenarios (II)-(V) with bioethanol production sections] vs. 1-ton cane sugar ethanol from a sugarcane biorefinery (economic allocation basis) [302]; (b) Sustainability index projections for the cassava wastes biorefineries for various weightings for LCC/eLCA metrics (0-80% for Case A; 0-75% for Case B) and fixed sLCA weighting (20% for Case A; 25% for Case B). In the figure, BAU = business-as-usual, C5EtOH = pentose based bioethanol, C5-C6EtOH = pentose + hexose based bioethanol, C6EtOH = hexose based bioethanol, CHP = combined heat and power, GS = glucose syrup, SA = succinic acid, eLCA = environmental life cycle assessment, LCC = life cycle costing, sLCA = social life cycle assessment

7.4.2 Economic performances of the biorefineries

Compared to the investment costs for the CHP scheme (I), higher (up to 1.84-folds) upfront cost impacts could be projected for the integrations of the CHP with bio-products [(II)-(V)] (Table 7.2), which could influence CWB choices regarding investment decisions. The BAU demonstrates the least capital investment cost (TCI), while the CWBs' generally increased (up to 1.84-folds) from scenario (I) to (V) (Table 7.2). Similar trends were shown for the production costs (TPC) (Table 7.2). The BAU scheme, therefore, presents the lowest investment costs requirements, but at the detriment of limiting the economic potentials for the cassava wastes. Comparing the NPV estimates for the CWBs (Table 7.2), the scenarios (I)-(II) demonstrate better investment returns than the BAU.

A shift from the BAU to the CWB systems that produce CHP only or with SA and/or bioethanol [i.e. (I), (II), (V)] can help advance industrial growths in the CSIs. The positive NPV projections for (I), (II) & (V) demonstrate their potentials for profitable investment returns and vice versa for (III) & (IV) (Table 7.2). Coupling profitability with the substantial surplus power generation capacities (~196-363 kWh/FU; Appendix D, Table D.1) for the (I), (II) & (V), their integrations into CSFs could help overcome the constraints of unreliable energy supplies & costs to the industrial crop prospects for cassava in leading cultivation nations such as Ghana [23] and Nigeria [12].

7.4.3 Social impact projections for the biorefineries

Collectively, an inconsistent trend was shown for the social impacts vs. the number of products in the CWBs, exemplified by the total sLCA projections (Table 7.2). The number of job creations correspond with the number of product integrations in the biorefineries [23-69 personnel, from BAU to (V); Table 7.2], which can be attributed to the matching increase in plant sections [296]. Conversely, comparable HTPs were projected for the (I)-(IV) [19.73-20.73 kg 1,4-DB eq; Table 7.2], with fairly similar contributions from their ash landfill treatments (~54.2%), CS transportation (~31.3%) and CWB inputs/emissions (~14.5%)

(SimaPro predictions). This can be explained by the comparable chemical inputs & emissions for the referred CWBs (Appendix D, Table D.1) and CS transportation considerations (section 7.3.2). Pertaining to the CWB's contribution to energy security, all scenarios [(I)-(V)] demonstrate substantial potentials for surplus power generation (~148-363 kWh/FU, Table 7.2), which decreased by up to ~59% for the scenarios co-producing CHP + bio-products [(II)-(V)] vs. CHP only (I) (Table 7.2).

7.4.4 Sustainability of the biorefineries

For all CWB scenarios, both the mutual investor-environmentalist (Case A) and the investor (Case B) stakeholder perspectives result in similar PSI trends with minor differences in magnitude (Fig. 7-8b), which suggests minimal differences in the impacts of the considered weightings on the PSIs. The Cases A & B baseline scenarios (section 7.3.3.2) showed comparable sustainability (PSI) rankings for the CWBs, with the predicted best-to-least scenario following the order (I) > (II) > BAU > (V) > (IV) > (III) (Fig. 7-8b). Additionally, the scenarios (I)-(II) favour the economic sustainability dimension than the environment's, and vice versa for the BAU, (III)-(V) (Fig. 7-8b). Under conditions of increasing the desired economic performance (i.e. increasing LCC weights) or decreasing the desired environmental performance (i.e. decreasing eLCA weights) (section 7.3.3.2), the predicted PSIs decreased for the BAU & (III)-(V), and increased for (I) & (II) (Fig. 7-8b). Therefore, under the context of demarcation of the system boundary at the biorefinery gate, the BAU scenario seemingly presents the best environmental scheme for the cassava starch wastes (Table 7.2), although with a negative consequence of limiting the economic potentials of the wastes (Table 7.2). For instance, comparing the NPV estimates in Table 7.2, the predicted order with regards to decreasing profitability potentials is (I) > (II) > BAU > (V) > (IV) > (III), which suggests scenarios (I) and (II) exhibit better economic incentives than the BAU.

From the TBL sustainability perspective, scenario (I) demonstrates greater incentives with higher economic gains and relatively low environmental impacts, followed by (II) > BAU > (V) > (IV) > (III) (Fig. 7-8b). Based on the ± magnitudes of the PSIs (Fig. 7-8b), scenarios (I), (II), BAU and (V) are promising for sustainable industrial expansions in CSIs, while the contrary is presented for scenarios (III)-(IV) (Fig. 7-8b). Considering the comparable environmental impacts for scenarios (III)-(IV) vs. (II) (Table 7.2), the non-sustainable tendencies of (III)-(IV) can be attributed to the downward economic performances, exemplified by their negative NPVs (Table 7.2).

Risks to the sustainability of the CWB scenarios (III) and (IV) would depend mainly on the economic profitability. For scenarios (III) & (IV), the considered Cases A & B both displayed possibilities to negate the sustainability when the weights of the economic categories are increased in the PSI tool (Fig. 7-8b). However, compared to the prevailing BAU scenario, the proposed uses of integrated cassava starch wastes for biorefinery conversions [(IV)-(V)] would result in increased environmental savings when the avoided GWP from the equivalent fossil-based products is taken into consideration (see Table 7.2), thus, enhanced environmental uses of the wastes. Furthermore, the additional SA in scenario (V) offers further opportunities to reduce fossil emissions and related adverse impacts through the replacement of succinic acid from petrochemical-derived maleic acid, thus, enhancing opportunities to transition from the fossil-based economies to bio-economies [54]. However, investment costs for such bioproduct technologies (e.g. SA) are reported to be higher than the fossil alternatives, resulting in their uncompetitive costs vs. the latter [48,49]. Active research to find cheaper approach and technology options are currently ongoing, with reports of promising trends shown regarding cost competitiveness in the long-term [49].

7.4.5 Reliability of the sustainability projections and avenues for future improvements

The sensitivity analysis (section 7.3.3.3) revealed the sub-metric weightings (Sc. 1-14) influence the sustainability rankings for the CWBs, especially the BAU and (I) which could switch positions (Fig. 7-9). Comparing the PSIs for the examined sub-metric weightings (Sc.1-14) vs. the 'Case A' baseline, the decreasing order of the biorefineries regarding robustness of the PSI to changes in the sub-metric weights was in the order: (V) > (II) > BAU > (I) > (IV) > (III) (Fig. 7-9). Scenarios (III) & (IV) were the most susceptible CWBs to changes in the sub-metric weights, with possibilities to reverse their sustainability (± PSI) (Fig. 7-9). Relative to the sustainability categories (i.e. LCC, eLCA, sLCA), the eLCA sub-metrics' weightings represent the main avenue to uncertainties in the PSIs, especially the TAP and FEP for scenario (III) (Fig. 7-9). Therefore, the considered sub-metric weightings in the LCSA, particularly the environmental category's, is crucial to the credibility of the estimated PSIs.

Future improvements of the PSI tool may target reliable sub-weight estimates, achievable through consensus building among related experts and stakeholders [293], and the use of advanced numerical tools that minimizes uncertainties in the outcomes such as the proposed Non-Linear Fuzzy Prioritization (NLFP) & interval multi-attribute decision analysis method [320]. In addition, the reliability of the PSI tool may be enhanced through the inclusion of other powerful sustainability indicators such as energy efficiency and exergy thermodynamic indicators [321]. Juxtaposed to the conventional energy analysis, which only shows how energy flows through a system, exergy analysis further identifies the avenues, magnitudes, and sources of process inefficiencies in energy and material conversion systems [322,323], such as the biorefinery system. Thus, exergy analysis presents superior thermodynamic performance indicator than the conventional energy analysis, and has gained popularity in sustainability assessments for biorefineries [321,324]. Integrations of the exergy analysis with related economic (exergoeconomic analysis) and environmental impact assessments (exergoenvironmental analysis) has proven useful for advanced and reliable sustainability assessments [325]. These sustainability approaches could, therefore, be explored in future sustainability evaluations for the CWBs.

7.5 Conclusions and future research

Comparative TBL sustainability assessment for CSI's conventional waste management (BAU scenario) and five CWB scenarios [(I) CHP, (II) C6EtOH+CHP, (III) C5-C6EtOH+CHP, (IV) C5EtOH+GS+CHP, and (V) C5EtOH+SA+CHP] has been achieved using a designed PSI estimation tool based on the principles of LCSA. The CWBs present better environmental uses for the wastes vs. the BAU, which could be enhanced by selecting biorefinery products with benign inputs or processing paths. Within the CWB gate boundaries, the environmental impacts generally increase with the number of products. However, allowing for the prospective avoided GHG emissions from the existing fossil-based equivalent products, the CWBs show potentials for higher environmental savings vs. the BAU.

Sustainability of the CWBs depend largely on the targets for the derived environmental or economic performances, with the scenarios (I)-(II) favouring the economic dimension vs. the environment's, and vice versa for the BAU, (III)-(V). Furthermore, positive PSI projections for the (I), (II), BAU & (V) revealed their potentials for sustainable developments in the starch industries, while the contrary was shown for scenarios (III)-(IV) (negative PSIs). The latter's unsustainable tendencies are attributable to the poor economic performances [NPVs, US$ -1 billion (III) & -388.5 million (IV)]. Hence, considering the potentials for substantial fossil emissions reductions and net power generation by the CWBs, governmental incentives of green power tariffs could enhance economic profitability of the CWBs for near-term applications. Implementation of the CWBs could, therefore, enhance sustainable industrial developments in CSIs.

The PSI tool could, therefore, provide preliminary decision support in the selection of sustainable CWB processes. Future research may focus on improving the reliability of the PSI tool via the incorporation of more dependable sustainability indicators (e.g. thermodynamic exergy), as well as establishing reliable weights for the indicators through stakeholder consensus and advanced numerical tools for minimizing uncertainties (e.g. Non-Linear Fuzzy Prioritization). Alternative reliable sustainability assessments tools (e.g. exergoeconomic & exergoenvironmental analysis) could also be explored for the CWBs.

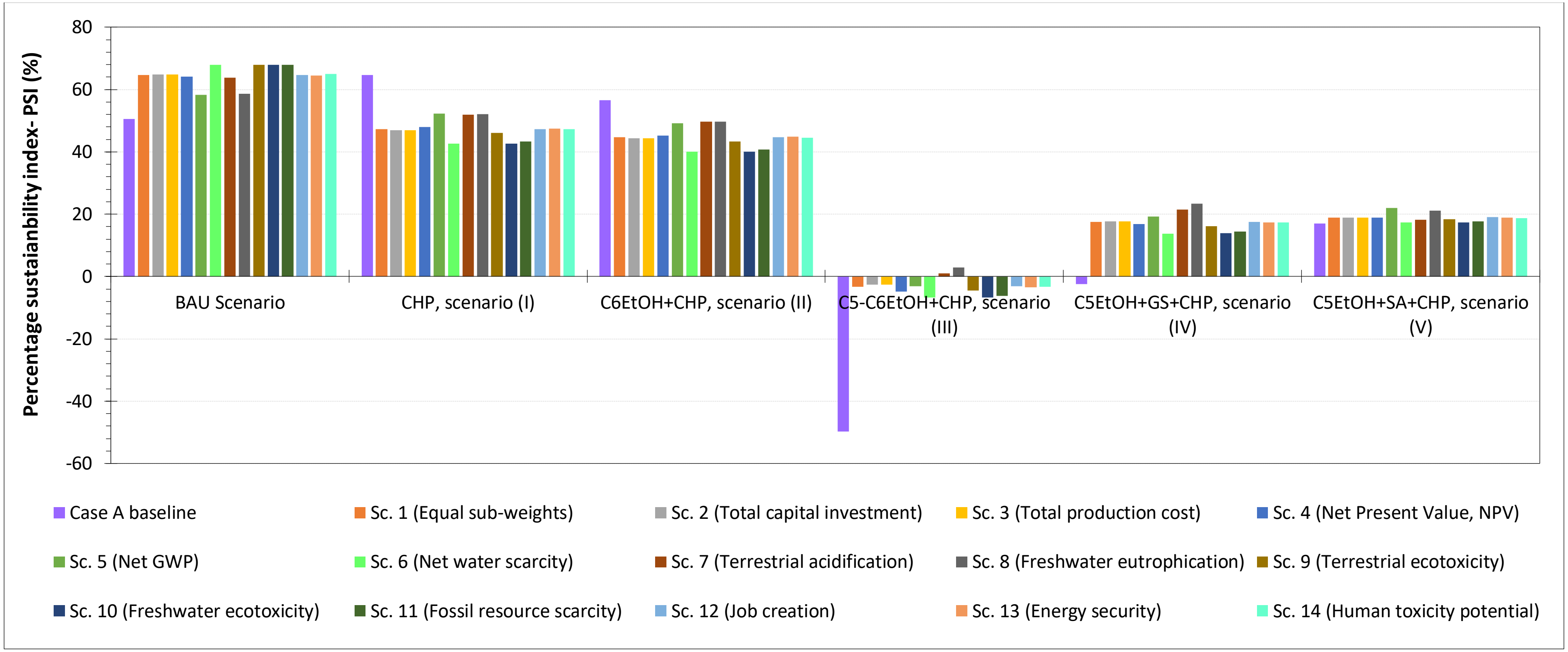


Fig. 7-9: Sensitivity assessments of the sub-metrics' weighting impacts on the sustainability index projections for the cassava wastes biorefineries. [NB: 'Case A baseline' scenario represents a 40% LCC, 40% eLCA & 20% sLCA weighting perspective, with the sub-weightings depicted in Table 7.2); Scenarios 1-14 (Sc.1-14) each represents prioritized weightings for the sub-metric (dominant sub-metric) in the bracket (see Appendix D, Table D.4)]. In the figure, BAU = business-as-usual, C5EtOH = pentose based bioethanol, C5-C6EtOH = pentose + hexose based bioethanol, C6EtOH = hexose based bioethanol, CHP = combined heat and power, GS = glucose syrup, SA = succinic acid, eLCA = environmental life cycle assessment, LCC = life cycle costing, sLCA = social life cycle assessment

8 Overall discussions and conclusions

8.1 Summary of the research outcomes

Integrated TEA, eLCA, and LCSA simulations have been used to analyze the technical feasibility and the sustainability (environmental, economic, and social) of cassava waste biorefineries (CWBs) for integration into prospective cassava starch facilities (CSF) in South Africa. Fig. 8-1 summarizes the specific research objectives, the CWB scenarios investigated, and the corresponding outcomes per the five (4) published/imminent research papers that emerged from the study (presented in Chapters 4-7). The salient research findings are discussed as follows.

8.1.1 Potential for integrated starch-bioenergy biorefineries for cassava versus established starch crops in South Africa

The study (Paper 1, Fig. 8-1) revealed that cassava and some established starch crops in South Africa (maize, sorghum, wheat, millet) may have potentials for co-production of starch and primary (field & process) residues-bioenergy (bioethanol or biogas) (see Table 4.5; section 4.5.5). Furthermore, projections for biogas from the conversions of the residues showed possibilities for sufficiency to meet the energy (electricity + thermal) needed to process the corresponding crops to starch/co-products, plus surplus electricity generation (397-4973 kWh/ha per annum). The residues-biogas conversion is, therefore, a possible strategy for energy self-sufficiency in starch industries (see Table 4.5; section 4.5.5). A shift from the conventional management regime for the starch crop residues (i.e. discard, burning, landfilling [82,83]) to the proposed uses of the total crops (main crop & residues) for integrated starch-bioenergy production could potentially enhance environmental (e.g. mitigation of pollution from residues disposal) and socio-economic (e.g. job & revenue expansions) developments in the starch industries.

8.1.2 Resource recovery potentials from integrated cassava starch wastes treatment

Diversity in the constitution of the wastes in the starch industries, such as the solid field wastes (e.g. CS) and the process wastes with high water fractions (e.g. CWW+CB), calls for strategic approaches to the practical implementation of the integrated starch and residues-bioenergy production systems. In this regard, the maturity and compatibility of the conversion technologies, logistic burdens (e.g. feedstock transportation costs for high moisture wastes), and related economic and environmental benefits are foreseeable key factors to the practical implementation [47,54]. Therefore, in the present study, a proven dual-fired (biomass, biogas) steam boiler/turbo-generator CHP technology [57,180] that is compatible with the existing starch wastes treatment schemes (AD of CWW+CB to produce biogas for starch drying heat plus disposal of the digestate into watercourses and burning of the CS) have been considered. Techno-economic simulations (Paper 2, Fig. 8-1) unraveled the potentials of the integrated CHP and conventional CSF waste treatment for enhancing the waste resource recoveries and economic returns for commercial investments. Compared to the present waste management scheme for a typical CSF (210 t starch/d), co-conversion of the CS (14.32 t/h) and CWW+CB into CHP demonstrated potentials for additional bioelectricity [31.96 MW (II); 9.63 MW (III)], biofertilizer [Liquid- 394 t/h (II); solid- 5 t/h (III)] and usable water [372.85 t/h (III)] recoveries. The resource recoveries could further ensure energy self-sufficiency in CSFs (II), as well as reductions (~66%) in freshwater requirements for CHP generation (III). Furthermore, the proposed resource recovery schemes (I-III) demonstrate profitable investments for commercial applications (NPVs of US$ 83.4-130 million). Such integrated CHP and waste treatment systems may help overcome the energy constraints to industrial CSF operations in the established cassava growing regions in Africa, such as Ghana [23] and Nigeria [12]. Hence, the proposed integration of CS wastes into the CSF's waste treatment can enhance the economic benefits from the total resource recoveries, which further could lessen the environmental footprints in the cassava industries.

8.1.3 Sustainability prospects for advanced biorefinery conversions of the cassava wastes

Advanced CWB conversions for the cassava starch wastes, including the co-production of CHP, SA and/or bioethanol using the integrated wastes [7.29 Mg/h DM CB + 377.83 Mg/h CWW + 450.89 Mg/h CS] are technically feasible. However, only CHP or integration with hexose-bioethanol (C6EtOH) demonstrate promises for advancing near-term sustainable industrial developments in the cassava industries (Paper 3, Fig. 8-1). The investigated CWB scenarios could supply the energy demands by the CWBs and CSFs, plus 300 MWh electricity (I), or 287 MWh + 1.48 Mg/h bioethanol (II), or 121 MWh + 8.95 Mg/h bioethanol (III), or 164 MWh + 5.72 Mg/h bioethanol + 9.29 Mg/h GS (IV), or 161 MWh + 5.72 Mg/h bioethanol + 6.9 Mg/h SA (V). From the economic assessments, only the scenarios (I)-(II) demonstrate the potentials for positive economic returns. Furthermore, relative to sustainability, the scenarios (I) & (II) favor the economic dimension of sustainability while the BAU & (III)-(V) favor the environment's (Paper 4, Fig. 8-1). The unviable investments for the scenarios (III)-(IV) [NPVs of US$ -1 billion (III) & -388.5 million (IV)] account for the referred sustainability trend.

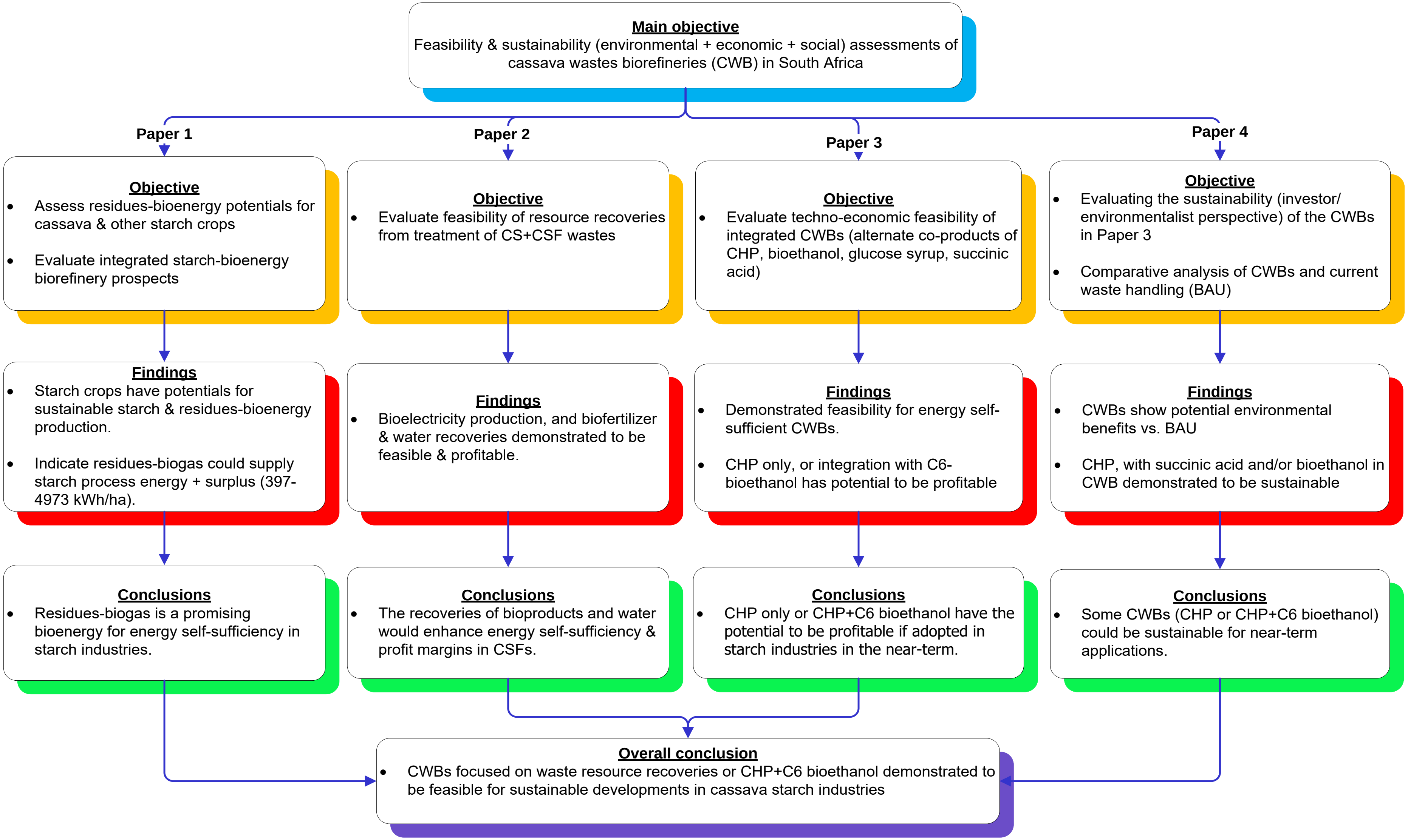


Fig. 8-1: Summary of the research objectives and outcomes

8.1.4 Potential of the cassava waste bioenergy for sustainable low-carbon economy developments in South Africa

Based on the predicted potentials for cassava as a sustainable feedstock for co-producing food-grade starch and residues-bioenergy (CHP, CHP+C6EtOH; Papers 2-4, Fig. 8-1), the industrial crop visions for cassava in South Africa [17] may consider such integrated starch and residues-bioenergy systems as possible means to advance both food-bioenergy security and low-carbon economy policies. The energy sector in South Africa reportedly accounts for over 80% of the national greenhouse gas emissions, due to the dominant fossil-based energy mix (e.g. 93% coal-power contributions to the total national power supply) [326]. Policies for transitioning to low-carbon green energy alternatives have been considered, including the Renewable Energy Independent Power Producer (REIPP) Procurement Programme [327]. However, implementation of the green energy agenda has been slow due to government's hesitations over impacts on the national development goals, taking into account the potential costs and social impacts (e.g. job losses in the well-established coal-based power sector) [70,326]. Prioritizing industrial developments with a drive for renewable energy uptake has been proposed as a possible avenue to advance sustainable green energy objectives, similar to the models applied by the developed countries (e.g. The Organization for Economic Co-operation and Development (OECD) countries) [326,327]. To this end, the cassava wastes bioenergy schemes (CHP & CHP+C6EtOH; Papers 2 & 3, Fig. 8-1) could serve the dual-purpose platform for advancing both the sustainable green energy goals and the industrial development goals (cassava industries). The referred energy schemes could provide environmental benefits relative to avoided impacts from corresponding fossil energy [e.g. Net GWP of -379 and -356 kg CO_2 for the CHP (I) and CHP+C6EtOH (II) respectively; Table 7.2, section 7.3.3.2] and socio-economic benefits (e.g. sustainable food-energy security, job creations and economic empowerment). Thus, the cassava wastes bioenergy schemes (CHP &

CHP+C6EtOH; Papers 2 & 3, Fig. 8-1) could be strategic for advancing the sustainable low-carbon development agenda of South Africa.

8.1.5 Conclusions

Industrialization of underdeveloped starch crops, such as cassava, can be enhanced and sustained via integrations with residues-bioenergy, which safeguards energy supplies for self-use, as well as boost the derived socio-economic developments. For instance, the starch-bioenergy schemes could motivate enhancements in job creations (e.g. CS feedstock collectors/suppliers), and economic gains by the farmers (sales of field residues) and starch processors (sales of surplus energy, biofertilizer etc.). Pertinent to CSFs, enhanced waste resource recoveries (CHP, biofertilizer, water) through integration of CS into the conventional waste (CWW+CB) treatment demonstrated viable potential for commercial investment. The resource recoveries could ensure beneficial circular economy schemes when the recovered resources are re-used in the CSFs and cassava cultivation, thereby supporting sustainable developments in the CSIs. Conversely, advanced biorefinery conversions of the integrated wastes (CB+CWW+CS) into multi-products (i.e. co-producing CHP+C5EtOH with GS or SA) were shown to be unviable for near-term applications, except for CHP co-produced with C6EtOH that demonstrated profitable investments and viable model for implementation considerations. Hence, integrations of CSIs with the resource recoveries or CHP+C6EtOH biorefinery conversions may be possible conduit to sustainable developments in the industry.

8.2 Practical implementation concerns for the identified viable cassava waste biorefinery schemes

8.2.1 Sustainable value chain concerns

From the research findings in sections 8.1.2 & 8.1.3, revitalization of cassava starch industries via integrations with the predicted viable CWBs (i.e. the resource recovery schemes, or the CHP+C6EtOH scheme) may enhance economic, environmental and social developments in the industry. Sustainable operations of the few industrial CSFs in Africa are reportedly constrained by multi-faceted challenges in the value-chain, including inadequate technical know-how, and unreliability in feedstock or process energy supplies. An example is the state-owned Ayensu Starch Factory in Ghana (see section 1.1.1.2), which has been operating erratically and inefficiently since its establishment in 2002, due to frequent breakdown of essential process equipment (e.g. the starch drier), and unreliable supplies of fuels and cassava feedstock for operations [34]. Such challenges of the host CSFs could invariably impact the sustainable operations of the CWBs. In addition, the CWB value chain (feedstock supply, biorefinery conversion technologies & logistics for operations, and products market) involves complex interdependent networks of operations and actors, which could further increase the risks to the sustainable CWBs [317]. For instance, the feedstock supply chain only (i.e. feedstock flow from the farmer/CSF to the CWB) consist of cultivation, mobilization, and transportation operations, where farmers and mobilization/transport labor are the major actors [54]. Furthermore, in the provinces identified suitable for cassava cultivation in South Africa, including KwaZulu-Natal, Eastern Cape, and Limpopo, farming is mainly a rural-based activity [4,17]. To mitigate the impacts of the low shelf-life and high transportation costs for the cassava feedstock, due to the high water contents (65-70 wt.%) [31], the host CSF and CWBs may be strategically located in close proximities to the rural cultivation areas. In-depth research on optimized value chain structures for the CSFs and CWBs, regarding cost-effectiveness and implementation risks mitigations, is, therefore, essential to their practical implementation and sustainable operations [54,317].

8.2.2 Sustainable feedstock supplies

Relative to the complexities of the value chain structures, the resource recovery CWBs are expected to be less susceptible to implementation risks vs. the scenario of CHP+C6EtOH production, thus, could be considered for near-term applications in existing CSFs. In the wastes resource recovery scenarios (section 8.1.2), the CWW+CB capacity projection was based on a typical 200 t starch/d CSF, whereas the CS (14.32 t/h) was limited to the generation capacities of the cassava farms that supply the cassava feedstock to the CSF (see section 5.2.1). In contrast, for the advanced CWB scenario (CHP+C6EtOH) (section 8.1.3), the CWW+CB capacities were projected similar to the resource recoveries', while ~3.18% and 96.82% of the considered CS capacities (450.89 t/h) were sourced from the host CSF's cassava feedstock farms and other farms respectively (see section 6.2.1.2). Therefore, feedstock security is foreseeable key feasibility determinant in the CHP+C6EtOH scenario vs. the resource recoveries. Outsourcing the mobilization and supply of the CS to private suppliers, in a manner similar to the existing CSF cassava feedstock supply chain [34,35], may encourage active partnerships for reliable feedstock deliveries to the CWBs. The CS price ($3.13/GJ) considered in the present study [sections 6.3.2.1] compares equitably with existing bioenergy feedstock prices (US$2.25-4/GJ) [274], thus, could be an ample incentive for the partnership investments. Furthermore, the maturity periods for cassava (from planting to harvesting) ranges between 6 months and 1 year, while the harvesting could be spanned between 6 months to 2 years from the day of planting [32]. Coupling the versatility of tolerance to diverse agro-ecological zones and the flexibility in harvesting periods and seasons [328], cassava could possibly be cultivated all year round [328], which may eliminate concerns of seasonality of the crop and related impacts on reliable CSF and CWB feedstock supplies. In relation to South Africa, the socio-economic impacts of allocating the feedstock cultivation land of 900 thousand ha (i.e. 7.2% of current available arable land [174], section 3.2.1) for cassava is imperative [245,246] and should be assessed in the governmental policies and industrial crop visions for cassava [17,45].

8.2.3 Technical risk considerations

Technical risks to the implementation of the predicted viable CWBs (i.e. resource recovery schemes, or CHP+C6EtOH scheme) will depend on the overall biorefinery configurations and maturity of the technologies [49]. Although laboratory demonstrations have shown potential for the various product conversions for the cassava starch wastes (Table 3.1, section 3.2.2), technical challenges or uncertainties may arise in their scale-up and integration into the commercial biorefinery complex [47,48]. For instance, identified technical obstacles for large-scale operations of dilute alkaline or ammonia fibre explosion (AFEX) pre-treatments include insufficient separation of lignin from cellulose and the formation of high amounts of inhibiting by-products to downstream fermentation [49]. Thus, consideration of demonstrated feasible industrial technologies in the CWB process designs is imperative to the commercial scale applications. In this regard, for the resource recovery CWB schemes (Paper 2, Chapter 5), the CHP and conventional waste treatment technologies (AD & water recovery) are well established with widespread commercial applications [57,72,180]. Similarly, the CHP+C6EtOH scheme (Paper 3, Chapter 6) consists of technologies that are advanced. For instance, with regard to the C6EtOH technology, similar starch-based C6EtOH technologies exists and are under industrial operations (e.g. corn based ethanol in the USA [49,57]). Hence, marginal technical risks to the commercial implementation could be anticipated for the predicted viable CWB scenarios in the present study. Pilot demonstrations are, however, essential for validating the simulation outcomes as well as identifying real-life technical obstacles for the referred CWBs. Sustainable operations of the CWBs may also require technical capacity and skills developments for the efficient operation of such sophisticated biorefinery technologies [47,49,329].

8.3 Recommendations for future research

The research outcomes contribute to knowledge on the potentials for cassava starch and related wastes biorefinery industries for South Africa, which could serve as a model for consideration in other cassava industries worldwide. In order to advance application of the findings, the following additional contexts are recommended for further investigations:

- In-depth assessments of the chemical and bacteriological compositions of the CWW+CB based liquid or solid digestate, in the proposed schemes for total resource recoveries from the waste treatments, should be performed to establish the compatibility with environmental/nutrients standards or further treatment requirements for biofertilizer applications.
- The predicted minimum energy prices (bioelectricity & starch drying hot air) from the simulated CWBs can impact the profitability of the starch processes vs. the present grid or fossil alternatives. This profitability impacts should be investigated for implementation decisions in the existing CSFs.
- The techno-economic assessments in the present study considered the CWBs and CSFs as separate stand-alone facilities, based on an independent private investor perspective, applicable to instances of already existing CSFs. However, the investment scenarios for a single facility of an integrated CSF and CWB will be interesting from a new investment viewpoint, as is the case for South Africa, and should, therefore, be investigated.
- The conceptualization and simulations of the biorefineries were based on available literature. Gaps in the literature on optimized pre-treatment and hydrolysis methods for the CS and/or CB compelled the present study to resort to adopting the available methods or making conservative assumptions. Optimized pretreatment and hydrolysis processes for the cassava wastes should, therefore, be established. The results should then be used to assess the profitability and sustainability impacts for the CWBs, towards ideal CWB process designs.

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Appendix

Appendix A

Appendix A.1: Sample calculation for the biomethane potential estimates for the crop residues

The biogas (biomethane) yields were estimated using the stoichiometric methane prediction formula developed by Buswell and Hartfield (Eq. A.1, [330]), and the residue compositions in Table 1):

$$C_xH_yO_z + \left(x - \frac{y}{4} + \frac{z}{2}\right) H_2O \rightarrow \left(\frac{x}{2} + \frac{y}{8} - \frac{z}{4}\right) CH_4 + \left(\frac{x}{2} - \frac{y}{8} + \frac{z}{4}\right) CO_2 \qquad \text{Eq. A.1}$$

Table 1: Compositions of the residues used to estimate the biogas (biomethane) potential

Crop	Residues	Glucan composition (g/100 g TS)	Hemicellulose composition (g/100 g TS)	References
Sorghum	Straw	41.9	26.7	[331]
	Shells	37.7	19.7	[190]
Millet	Stalks	27.9	18.5	[190,332]
Cassava	Stalk	67.1	28	[68,109,333]
	Peels	79	29.81	[209,334,335]
Maize	Stover	37.5	31.5	[57,207]
	Cobs	43	49.1	[190,336,337]
Potato	Peels	33.2	4.4	[248,338]
Wheat	Straw	39	30.1	[339,340]
	Chaff	32	27.3	[341,342]

Sample calculations (for sorghum straw):

From Eq. 1: Mole of biomethane yield from glucan is estimated as:

$C_{12}H_{25}NO_{11} \rightarrow 6.375\ CH_4$

Where: $C_{12}H_{25}NO_{11}$ is the glucan, molar mass = 359 g/mol; CH_4 is the biometahne; molar mass = 16 g/mol.

Thus, for 1 mol glucan => mass of CH_4 produced = (6.375 mol x 16 g/mol) = 102 g CH_4

From Table 1, 100 g TS sorghum straw contains 41.6 g glucans

For 100 g TS, mass of CH_4 => (41.9 g glucan/359 g glucan) x (102 g CH_4) = 11.91 g CH_4

Using CH_4 density (ρ) at STP value of 0.72 g/L, and ρ = m/v;

Volume of CH_4 per 100 g TS => (11.91 g/0.72 g.L^{-1}) = 16.54 L CH_4

Converting volume from L to m^3 => 16.54 Lx (0.001 m^3/ 1 L) = 0.01654 m^3 CH_4 per 100 g TS

Therefore, 1 ton TS => (10^6 g/100g) x 0.01654 m^3 CH_4 = **165.4 m^3 CH_4 per 1 ton TS**

Similarly, for the hemicellulose:

$C_5H_{10}O_5 \rightarrow 2.5\ CH_4$

Where: $C_5H_{10}O_5$ is the hemicellulose, molar mass = 150 g/mol; CH_4 is the biometahne; molar mass = 16 g/mol

Following the same approach as the glucan results in ~ **100 m^3 CH_4 per 1 ton TS**

For the considered residue to product ratio (RPR of 1.99; see Table 4.3, section 4.4.2) and annual crop yield per ha (2.5 t/ha; see Table 4.3, section 4.4.2):

Total sorghum straw per hectare => 1.99 x 2.5 t/ha = 4.975 t/ha

Therefore total CH_4 yield from sorghum straw per ha per annum cultivation:

=> 4.975 t/ha x (100 + 165.4 m^3 CH_4) = 1320.4 m^3 CH_4/ha per annum

Taking into account the presumed 80% process efficiency:

=>1302.7 m^3 CH_4/ha x 0.8 = ~**1056.3 m^3 CH_4/ha per annum**

Appendix A.2: Sample calculation for the surplus electricity potential from the residues-biogas (after supplying corresponding starch process energy)

Sample calculation (for sorghum):

Biogas obtained from sorghum straws (~1056.3 m^3 CH_4) and shells (~183 m^3 CH_4) amounts to ~ 1240 m^3 CH_4 /ha per annum crop cultivation (see b).

Thermal energy per hectare crop processing => 1269 MJ/t $_{\text{crop processed}}$ x 2.5 t $_{\text{crop}}$/ha

= 3172 MJ/ha $_{\text{crop processed}}$

(see Table 4.3, section 4.4.2; and Table 4.4, section 4.4.4)

Based on avg. calorific value of biogas (65% v/v CH_4) of 17.5 MJ/m^3; CH_4 calorific value (in the biogas) was estimated at 26.92 MJ/m^3 [247].

Volume of CH_4 needed to supply the thermal energy for the starch process:

=> 3172 MJ/ha ÷ 26.92 MJ/m^3

= 117.9 m^3 CH_4/ha

Surplus biogas after thermal energy supply => 1240 m^3 CH_4/ha - 117.9 m^3 CH_4

= ~1122 m^3 CH_4/ha

From 1 m^3 biogas (avg. 52.9 % v/v CH_4 content) yielding 2 KWh electricity via gas genset [247]:

Electricity potential of the surplus biogas (after thermal energy supply):

=> (1122 m^3 CH_4/ha ÷ 0.529 m^3 CH_4) x 2 kWh

= ~4243 kWh electricity

Surplus electricity (after supplying process electricity for the starch process):

=> 4243 kWh – (86 kWh/t $_{\text{crop processed}}$ x 2.5 t $_{\text{crop}}$/ha) [see Table 4.3, section 4.4.2; and Table 4.4, section 4.4.4]

= ~**<u>4030 kWh/ha per annum cultivation</u>**

Appendix A.3: Illustration of potential impacts of crop yields on the proposed multi-criteria framework for ranking the starch crops

- At 95% confidence level, the calculated standard deviations from the mean values of the crop yield (t/ha per annum) data (2006-2016, Fig. 4-1b) were: cassava (16.1 ± 1.61), maize (4.23 ± 0.42), millet (0.5 ± 0.01), potatoes (34.6 ± 0.59), wheat (3.2 ± 0.26), and sorghum (2.5 ± 0.35). The corresponding biogas and bioethanol projections for the lower and upper bounds are shown in Fig. A.1.
- To test for the potential impacts of the crop yields on the MCA rankings, the similar biogas yields for the 'upper bound value for maize' vs the 'mean value for cassava' (Fig. A.1) have been considered as a case study.
- Thus, the criteria in the MCA were estimated and compared for the mean crop yields for cassava and maize versus the upper bound for maize. The results, shown in Table A.1, suggest extreme variations (e.g. switch from the lower bound value to the upper bound value) in the individual crop yields could impact the MCA rankings, as shown by the switch in ranks for the surplus electricity criteria (Table A.1).

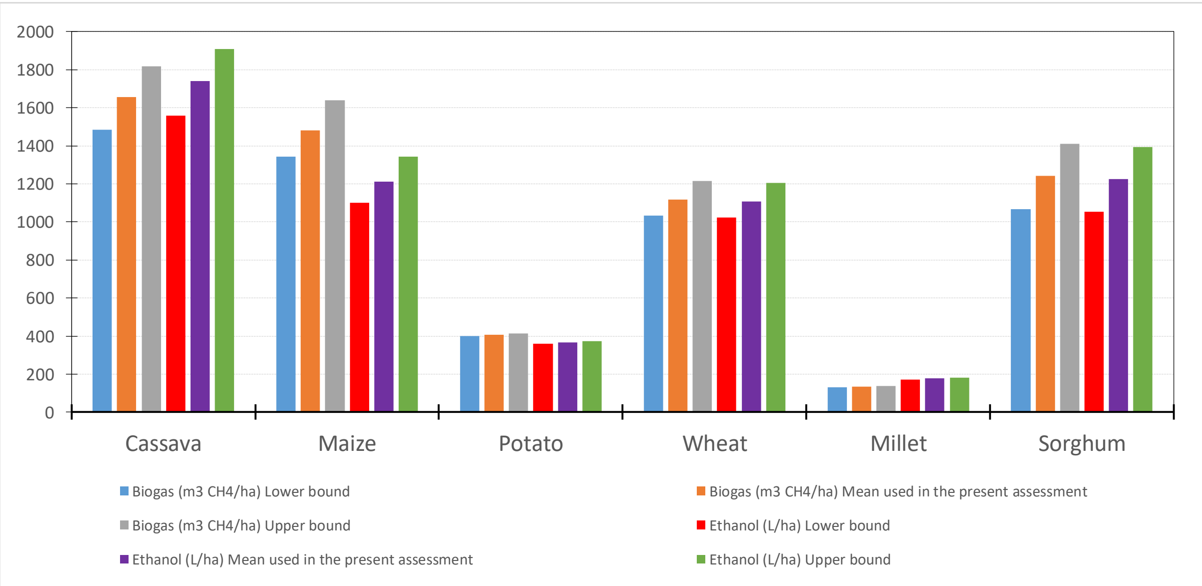

Fig. A. 1: Estimated bioethanol and biogas yields for crop yield ranges at 95% confidence level.

Table 1: The estimated criteria for the upper bound (95% confidence level) maize yield versus the criteria for the mean cassava and maize yields used for the assessment of impact of crop yields on the MCA ranking.

Crop yield considered	Theoretical biogas yield m^3 CH_4/ha	Theoretical ethanol yield (L/ha)	Surplus electricity after supplying starch process energies (kWh/ha)	Gross revenue contributions of residues based biogas to starch industry (%)	Gross revenue contributions of residues based bioethanol to starch industry (%)	Total gross revenue (theoretical biogas + starch/coproducts) ($/ha)	Total gross revenue (theoretical bioethanol + starch/coproducts) ($/ha)	Commercial starch yield (t/ha)
Cassava (mean value)	1656	1739	4319	8.15	14.78	2624	3810	3.28
Maize (Mean value)	1480	1212	4239	12.53	30.38	1526	2311	2.65
Maize (upper bound)	1640	1343	4696	12.21	41.54	1733	2603	2.94

Appendix B

Appendix B.1: Assumptions and calculations in estimating the rate of generation of the cassava starch wastes

Literature data and assumptions considered:

- Considered cassava starch process capacity of 200 t starch/d [71,72]
- 4.21 t cassava required to generate 1 t starch [44]
- 1 ton starch process generates 1.4 t cassava bagasse (CB) at 35-40% w/w moisture [44].
- 20% w/w of the generated cassava stalks (CS) used as planting materials [82], thus, only 80% of the generated CS are available for the integrated waste conversion process.
- CS-to-cassava root generation ratio of 0.51 [82]
- Average wastewater (CWW) per ton cassava processed = 10.875 m^3/t cassava processed [176]. Estimation of CWW mass flow (in this study) assumed the other components apart from water (see Table 5.1) have negligible weight relative to the water, thus, density of water (1000 kg/m^3) assumed for density of CWW.
- Cassava starch facility operates 24 h/d

Cassava bagasse (CB):

Wet CB generation rate (t/h) => (t CB generated / t starch produced) x (t starch produced/h)

=> (1.4 t CB/1 t starch) x (200 t starch/d) x (1 d/24 h) => 11.667 t wet CB/h

Dry mass (DM) CB generation rate (t/h) => (1 – average moisture) x (t wet CB/h)

=> [1-((0.35+0.4)/2)] x 11.667 t/h

=> **7.292 t_{DM} CB/h**

Cassava stalks (CS):

Total CS generation rate (t/h) => (t CS / t Cassava root required in starch process) = 0.51

=> 0.51 x t Cassava roots required in starch process

=> 0.51 x (4.21 t CS/t starch) x (200 t starch/d) x (1 d/24 h)

=>17.8925 t CS total/h

Available CS generation rate => 0.8 x Total CS generation rate

=> 0.8 x 17.8925 t CS/h

=> **14.314 t CS/h**

Cassava starch wastewater (CWW):

CWW generation rate (m^3/h) => (m^3 CWW/t Cassava) x (4.17 t Cassava / t starch) x (starch/h)

=> (10.87 m^3 CWW/ t Cassava) x (4. 17 t Cassava/ t Starch) x (200 t starch/ 24 h)

=> 377.83 m^3 CWW/h

CWW generation rate (t/h) => (CWW rate, m^3/h) x (Density, kg/m^3) x (1 t/1000 kg)

=> (377.83 m^3 CWW/h) x (1000 kg/m^3) x (1 t/1000kg)

=> **377.83 t CWW/h**

Table B.1: Summary of the stoichiometric reactions and conversions used to simulate the cassava starch wastes anaerobic digestion process in Aspen Plus®

Reaction number	Reaction extent: Reactant specified	Reaction extent: Fractional conversion (g/g)	Stoichiometry reactions from the Aspen simulation	Reference(s)
1	$NH_4ACETATE$	0.99	NH4ACETATE → $CH_4 + CO_2 + NH_3$	[57]
2	Lactic acid	0.85	2 Lactic acid → 3 CH_4 + 3 CO_2	[57]
3	Glycerol (MIXED)	0.85	Glycerol (MIXED) → 1.25 CO_2 + 1.75 CH_4	[57]
4	NH_4SO_4	0.98	NH_4SO_4 → H_2S + 2 NH_3 + 2 O_2	[57]
5	Cellulose (CISOLID)	0.4	Cellulose (CISOLID) + H_20 → Glucose	[57,262]
6	Cellulose (CISOLID)	0.1	Cellulose (CISOLID) + H_20 → 2 Ethanol + 2 CO_2	[57]
7	Hemicellulose (CISOLID)	0.02	Hemecellulose (CISOLID) + H_20 → Xylose	[57,262]
8	Xylose	0.5	Xylose → Acetic acid + 3 H2O	[262]
9	Hemicellulose (CISOLID)	0.4	Hemecellulose CISOLID) + H_20 → 2.5 Acetic acid	[262]
10	Starch (CISOLID)	0.3	Starch (CISOLID) + H_20 → Glucose	[262]
11	Triolein	1	Triolein + 0.04071 NH_3 + 0.0291 CO_2 + 1.90695 H_20 → 0.04071 Microbe + 0.9418 Propionic acid + 3 Oleic acid	[263]
12	Protein (CISOLID)	0.3	Protein (CISOLID) + 6 H_20 → 6.5 CH_4 + 6.5 CO_2 + 3 NH_3 + H_2S	[57]
13	Glucose	0.75	1.5 Glucose → 2 Propionic acid + Acetic acid + CO_2 + H_20	[57]
14	Ethanol	0.4	2 Ethanol + CO_2 → 2 Acetic acid + CH_4	[262]
15	Oleic acid (CISOLID)	0.7	Oleic acid (CISOLID) + 0.04071 NH_3 + 0.2501 CO_2 + 15.2396 H_20 → 0.04071 Microbe + 8.6998 Acetic acid + 14.4978 H_2	[262,263]
16	Propionic acid	0.5	Propionic acid + 0.06198 NH_3 + 0.314336 H_20 → 0.06198 Microbe + 0.9348 Acetic acid + 0.660412 CH_4 + 0.160688 CO_2 + 0.000552 Hydrogen	[262,263]
17	Acetic acid	0.7	Acetic acid + 0.022 NH_3 → 0.022 Microbe + 0.945 CH_4 + 0.945 CO_2 + 0.066 H_20	[262,263]
18	Hydrogen	0.5	14.4976 Hydrogen + 3.8334 CO_2 + 0.0836 NH_3 → 0.0836 Microbe + 3.4154 CH_4 + 7.4996 H_20	[262,263]

NB: The reactions occur in series. The fractional conversions were determined via a design specification block that ensured total organics in the effluent sums up to 15% w/w of the total organics fed to the AD reactor, thus, 85% COD removal [260]. The molar composition of the corresponding biogas, predicted at 0.46 CH_4 : 0.026 H_2 : 0.452 CO_2 : 0.058 H_2S, is similar to reports of 49.9-60.2% CH_4 contents for biogas from industrial cassava starch wastewater plus bagasse AD systems [72].

Table B.2: Assumptions in estimating the capital investment and operating costs for the cassava waste conversion processes

	Economic factors	Estimations/2018 values (US$ per kg)	Reference(s)
Capital investments	Total direct cost (TDC) [a]	103-107% of total installed costs [c]	[57,265]
	Total indirect cost (TIC) [b]	60% of TDC	[57,265]
	Fixed capital investment (FCI)	TDC + TIC	
	Working capital (WC)	5% of FCI	[57,265]
	Total capital investment (TCI)	FCI + WC + land	[57]
Operating costs		**Total variable costs (TVC)**	
	Delivered feedstock (CS only) [d]	0.051	[266,270]
	Flue gas desulfuriser lime	0.092	[343]
	Boiler chemicals	6.9165	[265]
	Cooling tower chemicals	4.145	[265]
	Waste disposal (mainly ash)	0.02886	[173,266]
	Process make-up water	0.00022	[173,266]
		Total fixed costs (TFC)	
	Total labour costs [e]		
	Labour burden	90% of labour costs	[57,265]
	Equipment depreciation	Linear depreciation; zero salvage value & 20 years recovery period	[178,185]
	Maintenance	2% of purchased equipment costs	[57]
		Plant overhead costs (POC)	
	Property insurance + tax	0.7% FCI	[57]
	Annual income tax	28% of only positive net income	[266]
	Total operating costs (TOC)	**TVC+TFC+POC**	

[a] TDC include total installed costs, warehouses, additional piping, and site development; [b] TIC comprise contingencies, field + construction expenses, start-up costs and permits; [c] Percentage estimates depends on the direct plant sections; [d] CB+CWW transportation costs factored into wastewater treatment charges (Table 5.2). CS delivered to the waste conversion facility was priced relative to its energy equivalents of coal [270]; [e] Labour requirements for each plant section was based on the study of Humbird et al. [57] with 8 major sections, thus, number of shift operators, supervisors & technicians were determined using proportionate plant sections, where number of sections for Case I = 2, Case II & III = 4. Labour salaries was estimated based on literature reports [173].

Table B.3: Breakdown of the Total Operating Costs (TOC) and revenues for the integrated cassava starch waste conversion processes

Components	**Case I**	**Case II**	**Case III**
	Total Operating Costs (TOC, US$ Million/a)		
Delivered CS feedstock	0.00	6.13	6.13
Boiler chemicals	0.00	0.00	0.00
Flue gas desulfurizer lime	0.02	0.02	0.02
Cooling tower chemicals	0.00	0.06	0.02
Makeup water	0.00	4.68	0.36
Disposal of ash/wastes	1.52	2.56	1.78
Additional electricity (import)	0.32	0.00	6.65
Total variable costs (TVC)	**1.86**	**13.45**	**14.95**
Labour	0.63	0.80	0.80
Labour burdens	0.56	0.72	0.72
Maintenance	0.02	0.21	0.21
Average equipment depreciation	1.59	4.77	4.33
Total fixed costs (TFC)	**2.80**	**6.50**	**6.06**
Property insurance + tax	0.33	1.00	0.91
Average annual income tax	3.88	7.54	6.08
Plant overhead costs (POC)	**4.21**	**8.55**	**6.99**
Total operating costs (TOC)	**8.87**	**28.50**	**28.00**
	Revenues (US$ Million/a)		
Liquid biofertilizer (I-II), Solid biofertilizer (III)	0.06	0.06	0.06
CWW treatment credit	21.61	21.61	43.21
RO brine mineral fertilizer	-	-	0.01
Hot air (starch drying)	0.78	0.78	0.78
Surplus biogas (I) or surplus bioelectricity (II)	0.37	30.76	-
Total annual revenues	**22.82**	**53.21**	**44.07**

Case I [CWW+CB conversion to thermal energy + liquid biofertilizer]; Case II [CWW+CB+CS conversion to CHP + liquid biofertilizer]; Case III [CWW+CB+CS conversion to CHP + solid biofertilizer + usable water]. CHP = combined heat and power, CS = cassava stalks, CWW = cassava starch wastewater, CB = cassava bagasse

Appendix C

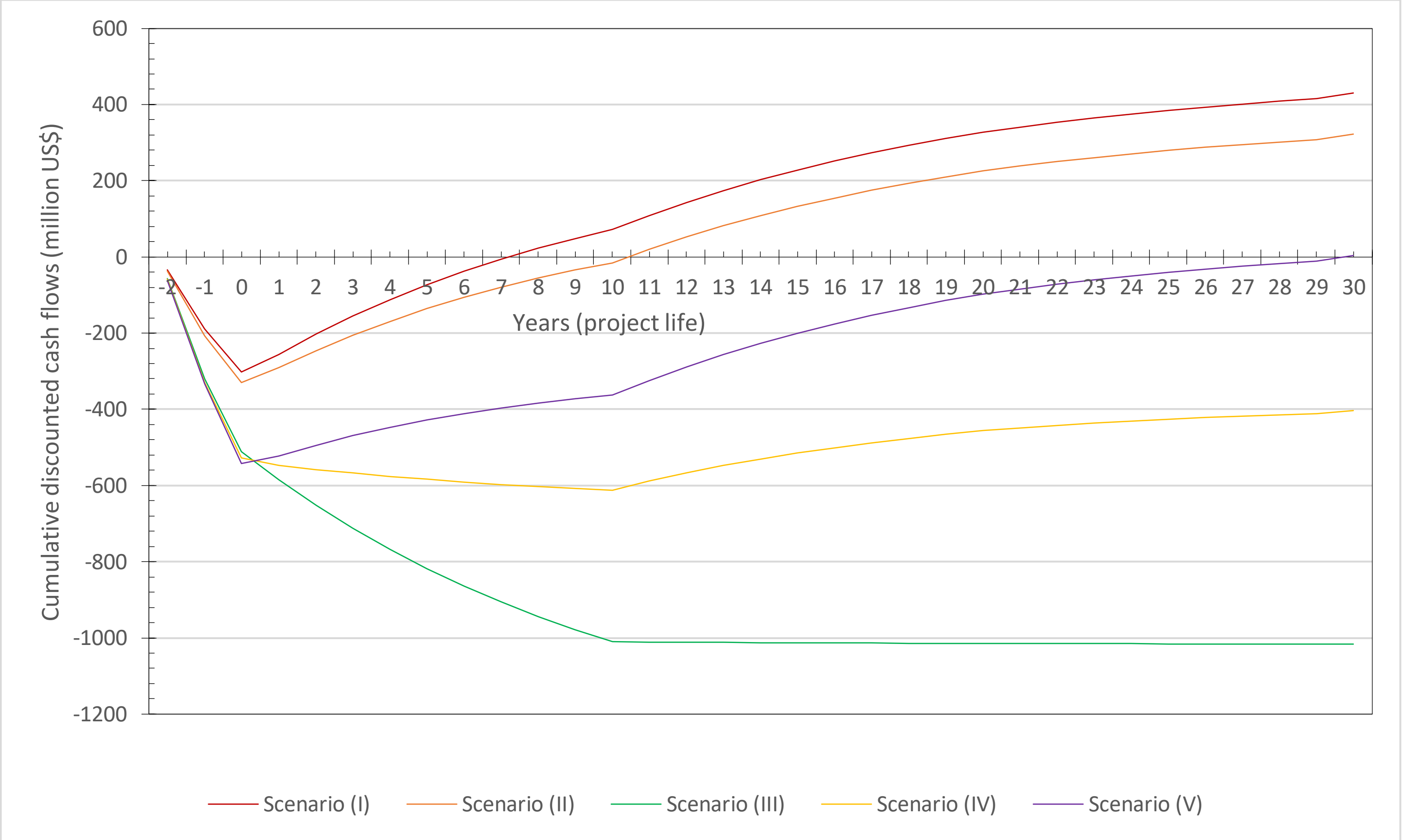

Fig. C.1: Cumulative discounted cash flow analysis (CDCFA) for the CWB scenarios (I-V) [NB: Projection based on following: 40% equity and 60% loan finance scheme [57,265]**; loan term specified at 8% interest and 10 years** [265]**; discount rate and inflation rate at 9.7% (real term) and 5.7% respectively** [266,270]**; 3-year engineering and construction period, having respective capital allocations of 10% (year -2), 60% (year -1) and 30% (year 0), and a 6-month start-up time** [265,266]**; linear equipment depreciation involving zero salvage value & 20 years recovery period** [265,266]**; certain equipment replaced occasionally (E.g. baghouse filter bag for boiler replaced after every 5 years** [57]**).**

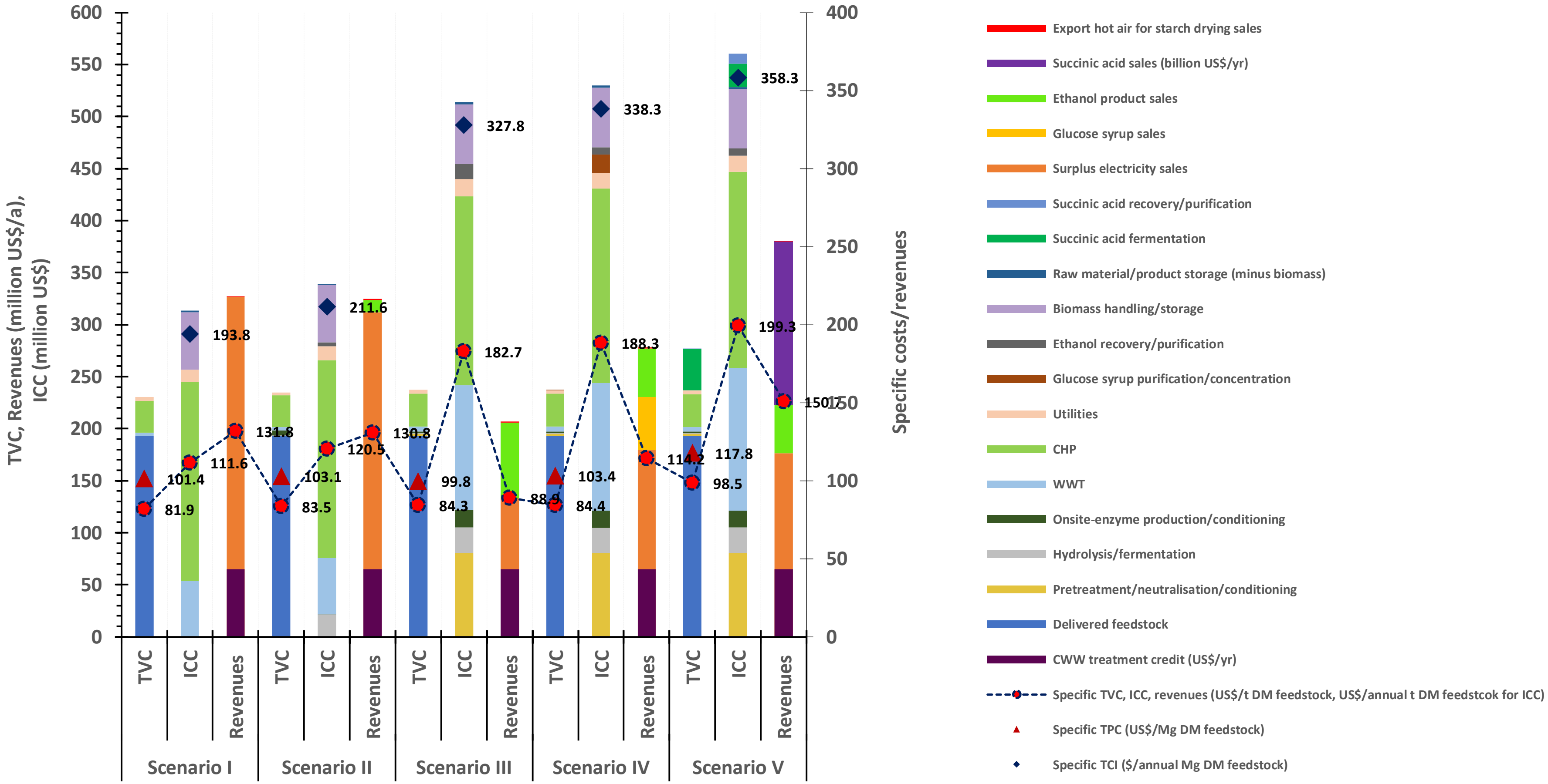

Fig. C.2: Key economic results for the biorefineries showing the Total Variable Costs (TVC) and Installed Capital Costs (ICC) per plant sections for the different scenarios of cassava waste biorefineries integrated in cassava starch processing, and related revenues. Where DM = dry matter, CS = cassava stalks, CB = Cassava bagasse, CWW = Cassava starch waste water, NREL= National Renewable Energy Laboratory and WWT = Waste water treatment

Table C.1: Reactions and mass conversions considered in the Aspen simulations

Pre-treatment in Scenario III, IV, V; based on [57,109]	Fractional conversion (g/g)	
Cellulose + H_2O → Glucose	0.503	
2Cellulose + H_2O → Cellobiose	0.03	
Cellulose → HMF + $2H_2O$	0.097	
Starch + H_2O → Glucose	0.57	
2Starch + H_2O → Cellobiose	0.009	
Starch → HMF + $2H_2O$	0.097	
Hemicellulose + H_2O → Xylose [a]	0.273	
Hemicellulose → Furfural + $2H_2O$ [a]	0.076	
Arabinan + H_2O → Arabinose	0.416	
Arabinan → Furfural + $2H_2O$	0.384	
Xylan + H_2O → Xylose	0.44	
Xylan → Furfural + $2H_2O$	0.1226	
Mannan + H_2O → Mannose	0.416	
Mannan → HMF + 2H2O	0.384	
Galactan + H_2O → Galactose	0.416	
Galactan → HMF + $2H_2O$	0.384	
Enzymatic hydrolysis. Scenario II based on [57,183]; Scenarios III, IV,V based on [57,109,209]	Fractional conversion (g/g)	
	Scenario II	Scenarios III, IV, V
2Glucan + H_2O → Cellobiose	0.0103	0.0116
Cellobiose + H_2O → 2Glucose	1	1
Glucan + H_2O → Glucose	0.9797	0.8684
Hemicellulose + H_2O → Xylose [b]	0.3	-
Hemicellulose → furfural + $2H_2O$ [b]	0.0349	-
Ethanol fermentation in Scenarios II, III, IV, V; adopted from [57]	Fractional conversions (g/g)	
	Seed production	Fermentation
Glucose → 2 Ethanol + 2 CO_2	0.9	0.95
Glucose + 0.047 CSL + 0.018 DAP → 6 Z. mobilis + 2.4 H_2O	0.04	0.02
Glucose + 2 H_2O → 2 Glycerol + O_2	0.004	0.004
Glucose + 2 CO_2 → 2 Succinic acid + O_2	0.006	0.006
3 Xylose → 5 Ethanol + 5 CO_2	0.8	0.85
Xylose + 0.039 CSL + 0.015 DAP → 5 Z. mobilis + 2 H_2O	0.04	0.019
3 Xylose + 5 H_2O → 5 Glycerol + 2.5 O_2	0.003	0.003
Xylose + H_2O → Xylitol + 0.5 O_2	0.046	0.046
3 Xylose + 5 CO_2 → 5 Succinic acid + 2.5 O_2	0.009	0.009
Succinic acid fermentation in Scenario V; based on [57,137,280]	Fractional conversions (g/g)	
	Seed production	Fermentation
Glucose + H_2O → 3 Acetic acid + H_2O	0.1	0.1
Glucose + 2 CO_2 → 2 Succinic acid + O_2	0.8	0.829
Glucose + 0.047 CSL + 0.018 DAP → 6 E. coli + 2.4 H_2O	0.082	0.067
2 Xylose + H_2O → 5 Acetic acid + H_2O	0.09	0.09
3 Xylose + 5 CO_2 → 5 Succinic acid + 2.5 O_2	0.8	0.829
Xylose + 0.039 CSL + 0.015 DAP → 5 E. coli + 2 H_2O	0.079	0.067
2 Arabinose → 5 Acetic acid + H_2O	0.09	0.09
3 Arabinose + 5 CO2 → 5 Succinic acid + 2.5 O2	0.8	0.829
Arabinose + 0.039 CSL + 0.015 DAP → 5 E.coli + 2 H2O	0.079	0.067

[a] Applicable to Cassava bagasse (CB) only, based on assumption that the xylan content is same as cassava stalk- 8.2% g/g [109]; [b] In the adopted study [183], high hemicellulose activity of the Novozyme® NS 50012 was cited as a contributing factor for the high sugar yield. Accordingly, 30% (g/g) hemicellulose conversion to xylose was projected in balancing the sugar yields. CSL = Corn steep liquor; DAP = Diammonium phosphate

Table C.2: Assumptions in estimating the production costs and product prices

	Parameters	2018 prices (US$/kg, US$/kWh electricity)	Scenarios (Million US$/a)				
			I	II	III	IV	V
Production costs	Delivered feedstock [a]	0.051	193.05	193.05	193.05	193.05	193.05
	Ammonia [b]	0.442	-	0.0029	1.31	1.31	1.22
	Corn steep liquor [c]	0.079	-	0.0706	0.23	0.18	0.25
	Glucose [d]	0.853	-	0.1267	1.69	1.69	1.69
	Enzyme nutrients [d]	1.138	-	0.00365	0.05	0.05	0.05
	Sorbitol [e]	1.195	-	0.12	0.12	0.12	0.17
	Sulphur dioxide [d]	0.082	-	0.00008	0.001	0.001	0.001
	Purchased enzymes [f]	10.54	-	4.82	-	-	-
	Activated carbon [g]	0.6	-	-	-	0.44	0.44
	Total labour costs [h]		0.80	1.05	1.29	1.37	1.46
Revenue	Sellable electricity (surplus) [i]	0.1282	326.758	311.804	133.035	179.481	176.361
	Glucose syrup [j]	0.6532	-	-	-	51.018	-
	Ethanol product [k]	0.985	-	12.032	72.912	46.588	46.586
	Export hot air for starch drying [l]	0.0005	0.778	0.778	0.778	0.778	0.778
	CWW treatment credit [m]	0.0136	43.214	43.214	43.214	43.214	43.214

[a] CB+CWW transport costs factored into wastewater treatment credits (see item 'm' below). Delivered CS price was based on energy equivalents of coal [270]; [b] Total demands for neutralisation (341 kg/h) and enzyme production (10 kg/h for Scenarios III, IV, V); [c] Sum of demands in ethanol fermentation (101, 329, 254, 252 kg/h) and enzyme production (0, 12, 12, 12 kg/h) for Scenarios II-V, respectively, plus succinic acid fermentation in Scenario V (110 kg/h); [d] Used in onsite enzyme production- based on Humbird et al. [57]; [e] Used in bioethanol fermentation [57]; [f] Relevant to Scenario II's enzyme cocktail of α-amylase (0.2% g/g), glucoamylase (0.066% g/g), and cellulase (0.4% g/g) [109], at respective quotes of $10/kg, $6/kg, and $11.51/kg (average quotes); [g] Assumed replacement after every 6 months [266], [h] Number of labour based on Humbird et al. [57] which had 8 major sections- number of technicians, shift operators + supervisors based on proportionate plant sections (I = 4, II = 7, III = 8, IV = 9, V = 10), and labour costs based on Gorgens et al. [173]; [i] Estimated as 20% higher than coal power price of 0.1068 US$/kWh (www.eskom.co.za), which conforms with South Africa's commitment to green electricity [270]; [j] Average reports by local wholesale suppliers; [k] Estimated as gasoline energy equivalent (0.7 L gasoline = 1 L bioethanol) and average local gasoline price of 1.11 US$/L (www.globalpetrolprices.com); [l] Valued as sum of costs of corresponding coal fuel on energy basis- [(27142 MJ/hr x 0.08$/kg coal)/23.25 MJ/kg coal] ($93.40/h), flue economiser's depreciation ($0.45/h) and associated labour cost ($0.35/h); [m] Estimated as 80% of avg. wastewater treatment costs (0.001-0.033$/L) for South Africa [258], while assuming the 20% offsets costs of pumping the CB+CWW to the biorefinery. Scenario I [CB+CWW+CS CHP]; Scenario II [CB+CWW bioethanol/100% CS CHP]; Scenario III [CS+CB+CWW bioethanol/90% CS CHP]; Scenario IV [CS+CB+CWW GS/bioethanol/90% CS CHP]; Scenario V [CS+CB+CWW SA/bioethanol/90% CS CHP]. Where CS = cassava stalks, CB = Cassava bagasse, CWW = Cassava starch wastewater, CHP = Combined Heat and Power

Appendix D

Table D.1: Primary life cycle inventory data for the cassava wastes biorefineries. The values per functional unit (FU) are calculated based on Aspen Plus® simulated mass and energy balances from previous studies [299,344]

		Cassava wastes biorefinery scenarios					
Materials	**Units**	**BAU** [a]	**(I)** [b]	**(II)** [b]	**(III)** [b]	**(IV)** [b]	**(V)** [b]
A. INPUTS							
Cassava stalks (CS)	kg (75% DM)/FU	539.34	539.34	539.34	539.34	539.34	539.34
Cassava bagasse (CB)	kg DM/FU	8.72	8.72	8.72	8.72	8.72	8.72
Cassava starch wastewater (CWW)	kg/FU	451.94	451.94	451.94	451.94	451.94	451.94
Water (total make-up water)	kg/FU	-	1878.22	1410.94	2051.76	1911.17	2030.35
Total imported process electricity (coal grid power)	kWh/FU	0.43	-	-	-	-	-
Pre-treatment							
Pre-treatment H_2SO_4	kg/FU	-	-	-	1.20	1.20	1.20
Hydrolysate conditioning NH_3	kg/FU	-	-	-	0.44	0.44	0.41
Enzymes (activation/production)							
Purchased alpha-amylase (0.2% w/w)	kg/FU	-	-	1.96E-02	-	-	-
Purchased glucoamylase (0.066% w/w)	kg/FU	-	-	6.47E-03	-	-	-
Purchased cellulase (0.4% w/w)	kg/FU	-	-	3.92E-02	-	-	-
Enzyme activation (CNUTR)	kg/FU	-	-	4.56E-04	-	-	-
Enzyme activation (NH_3)	kg/FU	-	-	8.82E-04	-	-	-
Enzyme activation (SO_2)	kg/FU	-	-	1.33E-04	-	-	-
Seed Enzyme production (Glucose)	kg/FU	-	-	-	2.60E-01	2.60E-01	2.60E-01
Seed Enzyme production (Ammonia)	kg/FU	-	-	-	6.15E-04	6.15E-04	6.15E-04
Seed Enzyme production (CSL)	kg/FU	-	-	-	5.33E-04	5.33E-04	5.33E-04
Seed Enzyme production (SO_2)	kg/FU	-	-	-	5.26E-05	5.26E-05	5.26E-05
Enzyme production (Corn oil antifoam)	kg/FU	-	-	-	1.07E-03	1.07E-03	1.07E-03
Enzyme production (CSL)	kg/FU	-	-	-	1.41E-02	1.41E-02	1.41E-02
Enzyme production (CNUTR)	kg/FU	-	-	-	6.07E-03	6.07E-03	6.07E-03
Enzyme production (NH_3)	kg/FU	-	-	-	1.18E-02	1.18E-02	1.18E-02
Enzyme production (SO_2)	kg/FU	-	-	-	1.77E-03	1.77E-03	1.77E-03
Ethanol fermentation							
Z. mob seed production (CSL)	kg/FU	-	-	2.19E-02	7.14E-02	5.53E-02	7.14E-02
Z. mob seed production (DAP)	kg/FU	-	-	2.72E-03	7.99E-03	6.38E-03	6.30E-03
Ethanol fermentation (DAP)	kg/FU	-	-	1.20E-02	3.54E-02	2.83E-02	2.79E-02
Ethanol fermentation (CSL)	kg/FU	-	-	9.87E-02	3.21E-01	2.49E-01	3.21E-01
Succinic acid fermentation							
SA E.coli-seed production (CSL)	kg/FU	-	-	-	-	-	2.19E-02
SA E.coli seed production (DAP)	kg/FU	-	-	-	-	-	3.45E-03
SA fermentation (CSL)	kg/FU	-	-	-	-	-	1.31E-01
SA fermentation (DAP)	kg/FU	-	-	-	-	-	1.53E-02
SA fermentation (NaOH)	kg/FU	-	-	-	-	-	24.61
SA fermentation (H_2SO_4)	kg/FU	-	-	-	-	-	29.44
Boiler water chemicals							
Sodium Phosphate (scale prevention)	kg/FU	-	9.03E-05	1.18E-04	9.03E-05	1.43E-03	1.44E-03
Morpholine (Neutralizing amine)	kg/FU	-	9.03E-05	1.18E-04	9.03E-05	1.43E-03	1.44E-03
Sodium hydroxide (Alkalinity control)	kg/FU	-	9.03E-05	1.18E-04	9.03E-05	1.43E-03	1.44E-03
Sodium sulfite (Oxygen scavenger)	kg/FU	-	9.03E-05	1.18E-04	9.03E-05	1.43E-03	1.44E-03
Cooling tower chemicals							
Phosphoric acid	kg/FU	-	5.01E-03	5.10E-03	5.01E-03	6.60E-03	6.40E-03
Bromine	kg/FU	-	5.01E-03	5.10E-03	5.01E-03	6.60E-03	6.40E-03
Sodium bicarbonate	kg/FU	-	5.01E-03	5.10E-03	5.01E-03	6.60E-03	6.40E-03
50% Caustic (Aerobic digestion)	kg/FU	-	4.29	4.33	5.993	6.212	6.075
Flue gas cleaning (20% Lime solution)	kg/FU	-	0.75	0.79	5.837	5.826	5.837
B. OUTPUTS							
Starch drying hot air	kg/FU	221.29	221.29	221.29	221.29	221.29	221.29
Net electricity	kWh/FU	-	362.52	345.93	147.59	199.12	195.67
Bioethanol (99.5% ethanol)	kg/FU	-	-	1.77	10.71	6.84	6.84
Glucose syrup (70% w/w)	kg/FU	-	-	-	-	11.11	-
Succinic acid (98.1% w/w)	kg/FU	-	-	-	-	-	8.26
Surplus biogas (from CWW+CB AD)	kg/FU	1.60	-	-	-	-	-
Air emissions [c]							
Boiler/combustor flue gases	kg/FU	24.03	445.04	443.14	425.87	423.96	426.01
Aerobic digestion (air emissions)	kg/FU	-	0.44	0.31	1.30	1.38	1.51
Cellulase enzyme activation/production (air emissions)	kg/FU	-	-	1.70E-02	2.27E-01	2.27E-01	2.27E-01
Ethanol venturi scrubber (air emissions)	kg/FU	-	-	1.681	9.955	6.322	-
Succinic acid fermenter (air emissions)	kg/FU	-	-	-	-	-	0.328
SA seed fermenter (flash vapor)	kg/FU	-	-	-	-	-	1.546
SA evaporation (air discharge)	kg/FU	-	-	-	-	-	1.19E-02
Flue gas from stalk burning	kg/FU	445.15	-	-	-	-	
Boiler/baghouse filter ash + solids	kg/FU	7.50	163.15	162.50	150.48	150.48	316.60
SA ferment broth solids (CELLDSP)	kg/FU	-	-	-	-	-	0.83
Ash from stalk burning	kg/FU	162.90	-	-	-	-	-
CWW+CB digestate (AD effluent)							
Water	kg/FU	4.46E+02	-	-	-	-	-
Propionic acid	kg/FU	1.49E-02	-	-	-	-	-
NH_3	kg/FU	2.73E+00	-	-	-	-	-
Xylose	kg/FU	8.33E-04	-	-	-	-	-
Ethanol	kg/FU	1.53E-04	-	-	-	-	-
Cyanide	kg/FU	1.57E-03	-	-	-	-	-
Acetic acid	kg/FU	4.20E-02	-	-	-	-	-
Diammonium phosphate	kg/FU	6.34E-02	-	-	-	-	-
Cellulose	kg/FU	4.84E-02	-	-	-	-	-
Hemicellulose	kg/FU	5.39E-02	-	-	-	-	-
Starch	kg/FU	6.72E-01	-	-	-	-	-
Lignin	kg/FU	1.18E-01	-	-	-	-	-
Microbe	kg/FU	1.76E-01	-	-	-	-	-
Ash	kg/FU	1.04	-	-	-	-	-

[a] Estimates based on previous work [344]; [b] Estimates adopted from previous work [299]; [c] Excludes H_2O vapor and N_2+O_2 (from 21% excess stoichiometric air supplied in the combustion) deemed irrelevant regarding environmental impacts; Scenarios: (I)- CHP, (II)- C6EtOH + CHP, (III)- C5-C6EtOH+CHP, (IV)- C5-C6EtOH+GS+CHP, (V)- C5EtOH+SA+CHP. AD = anaerobic digestion, BAU = business-as-usual, C5EtOH = pentose based bioethanol, C5-C6EtOH = pentose + hexose based bioethanol, C6EtOH = hexose based bioethanol, CHP = combined heat and power, CNUTR = cellulase nutrient mix, CSL = corn steep liquor, DAP = diammonium phosphate, DM = dry mass, FU = functional unit (defined as biorefinery converting 1-ton collective feedstock, comprising (w/w) 45.2% CWW + 0.9% CB + 53.9% CS), GS = glucose syrup, SA = succinic acid

Table D.2: Projected revenues for the biorefinery products and corresponding economic allocation factors considered in the life cycle impact assessments

Products	Prices (US$/kg; US$/kWh)	BAU R (million US$/a) [g]	BAU AF	Scenario (I) R (million US$/a) [h]	Scenario (I) AF	Scenario (II) R (million US$/a) [h]	Scenario (II) AF	Scenario (III) R (million US$/a) [h]	Scenario (III) AF	Scenario (IV) R (million US$/a) [h]	Scenario (IV) AF	Scenario (V) R (million US$/a) [h]	Scenario (V) AF
SDHA	0.0005 [a]	0.778	0.678	0.778	0.002	0.778	0.002	0.778	0.004	0.778	0.003	0.778	0.002
Surplus biogas	0.0328 [b]	0.37	0.322	-	-	-	-	-	-	-	-	-	-
Bioethanol	0.985 [c]	-	-	-	-	12.032	0.038	72.912	0.355	46.588	0.169	46.586	0.124
Net electricity	0.1282 [d]	-	-	326.758	0.998	311.804	0.960	133.035	0.641	179.481	0.645	176.361	0.463
Glucose syrup	0.653 [e]	-	-	-	-	-	-	-	-	51.018	0.183	-	-
Succinic acid	2.7 [f]	-	-	-	-	-	-	-	-	-	-	156.869	0.412

[a] Calculated as sum of price of coal energy equivalent ($93.40/h) [(27142 MJ/h x 0.08$/kg coal)/23.25 MJ/kg coal]], depreciation charges for flue economiser ($0.45/h) & related workforce charges ($0.35/h); [b] Valuation based on corresponding LPG energy (0.2 kg LPG = 1 kg biogas) and price of $0.164/kg LPG for South Africa [234]; [c] Valued based on corresponding gasoline energy (0.7 L gasoline = 1 L bioethanol) and avg. gasoline price of 1.11 US$/L (www.globalpetrolprices.com); [d] Evaluated as 20% in excess of price for coal power (0.1068 US$/kWh; www.eskom.co.za) [272], justified by national aspirations of shift towards green power in South Africa [270]; [e] Avg. price quotes by wholesalers in South Africa; [f] Avg. literature reports [49,281]; [g] Projections detailed in previous work [344]; [h] Details of the estimates presented in previous study [299]; Scenarios: (I)- CHP, (II)- C6EtOH + CHP, (III)- C5-C6EtOH+CHP, (IV)- C5-C6EtOH+CHP, (V)- C5EtOH+SA+CHP. AF = economic allocation factor, BAU = business-as-usual, C5EtOH = pentose based bioethanol, C5-C6EtOH = pentose + hexose based bioethanol, C6EtOH = hexose based bioethanol, CHP = combined heat and power, GS = glucose syrup, SA = succinic acid, SDHA = starch drying hot air, R = revenues from product sales

Table D.3: The adopted fossil based alternative processes from the Ecoinvent database used for the projections of the net global warming potentials (Net GWP) and net water scarcity (NWS)

<table>
<tr><th>Cassava wastes biorefinery scenarios</th><th>Biorefinery products/FU [a]</th><th>Equivalent fossil products/processes considered in the Net GWP and NWS projections</th><th>The adopted fossil-based products from the Ecoinvent database [302]</th></tr>
<tr><td>BAU</td><td>221.29 kg starch drying hot air- SDHA (170 °C); 1.6 kg surplus biogas</td><td>32.47 MJ Fossil-light oil based industrial heat using furnace; 0.32 kg Fossil-LPG</td><td>Heat, district or industrial, other than natural gas {RoW}| heat production, light fuel oil, at industrial furnace 1MW | Cut-off, U; Liquefied petroleum gas {RoW}| petroleum refinery operation | Cut-off, U</td></tr>
<tr><td>(I)- CHP</td><td>221.29 kg SDHA; 362.52 kWh electricity</td><td>32.47 MJ Fossil-light oil based industrial heat using furnace; 362.52 kWh Fossil-coal electricity for South Africa</td><td>Heat, district or industrial, other than natural gas {RoW}| heat production, light fuel oil, at industrial furnace 1MW | Cut-off, U; Electricity, high voltage {ZA}| electricity production, hard coal, conventional | Cut-off, U</td></tr>
<tr><td>(II)- C6EtOH + CHP</td><td>221.29 kg SDHA + 345.93 kWh electricity + 1.77 kg bioethanol</td><td>32.47 MJ Fossil-light oil based industrial heat using furnace; 345.93 kWh Fossil-coal electricity for South Africa; 1.77 kg Fossil-based ethanol</td><td>Heat, district or industrial, other than natural gas {RoW}| heat production, light fuel oil, at industrial furnace 1MW | Cut-off, U; Electricity, high voltage {ZA}| electricity production, hard coal, conventional | Cut-off, U; Ethanol, without water, in 99.7% solution state, from ethylene {RoW}| ethylene hydration | Cut-off, U</td></tr>
<tr><td>(III)- C5-C6EtOH+CHP</td><td>221.29 kg SDHA + 147.59 kWh electricity + 10.71 kg bioethanol</td><td>32.47 MJ Fossil-light oil based industrial heat using furnace; 147.59 kWh Fossil-coal electricity for South Africa; 10.71 kg Fossil-based ethanol</td><td>Heat, district or industrial, other than natural gas {RoW}| heat production, light fuel oil, at industrial furnace 1MW | Cut-off, U; Electricity, high voltage {ZA}| electricity production, hard coal, conventional | Cut-off, U; Ethanol, without water, in 99.7% solution state, from ethylene {RoW}| ethylene hydration | Cut-off, U</td></tr>
<tr><td>(IV)- C5-C6EtOH+GS+CHP [b]</td><td>221.29 kg SDHA + 199.12 kWh electricity + 6.84 kg bioethanol + 11.11 kg glucose syrup</td><td>32.47 MJ Fossil-light oil based industrial heat using furnace; 199.12 kWh Fossil-coal electricity for South Africa; 6.84 kg Fossil-based ethanol; 11.11 kg Fossil-energy (electricity/heat) driven glucose syrup process</td><td>Heat, district or industrial, other than natural gas {RoW}| heat production, light fuel oil, at industrial furnace 1MW | Cut-off, U; Electricity, high voltage {ZA}| electricity production, hard coal, conventional | Cut-off, U; Ethanol, without water, in 99.7% solution state, from ethylene {RoW}| ethylene hydration | Cut-off, U; Glucose {RoW}| glucose production | Cut-off, U</td></tr>
<tr><td>(V)- C5EtOH+SA+CHP [c]</td><td>221.29 kg SDHA + 195.67 kWh electricity + 6.84 kg bioethanol + 8.26 kg succinic acid</td><td>32.47 MJ Fossil-light oil based industrial heat using furnace; 195.67 kWh Fossil-coal electricity for South Africa; 6.84 kg Fossil-based ethanol; 8.26 kg Fossil-based succinic acid</td><td>Heat, district or industrial, other than natural gas {RoW}| heat production, light fuel oil, at industrial furnace 1MW | Cut-off, U; Electricity, high voltage {ZA}| electricity production, hard coal, conventional | Cut-off, U; Ethanol, without water, in 99.7% solution state, from ethylene {RoW}| ethylene hydration | Cut-off, U; Succinic acid {GLO}| succinic acid production | Cut-off, U</td></tr>
</table>

[a] All the biorefinery processes are energy (heat/electricity) self-sufficient, except the BAU's process electricity that is supplied by grid coal-power (see Appendix, Table C.1); [b] The fossil data for glucose syrup (GS) from the Ecoinvent database presumes a starch-based glucose production process, with the process heat predominantly based on natural gas (fossil) and the electricity based on coal (fossil); [c] The fossil-based succinic acid from the Ecoinvent database is based on the hydrogenation of fossil-based maleic acid process. Scenarios: (I)- CHP, (II)- C6EtOH + CHP, (III)- C5-C6EtOH+CHP, (IV)- C5-C6EtOH+GS+CHP, (V)- C5EtOH+SA+CHP. AD = anaerobic digestion, BAU = business-as-usual, C5EtOH = pentose based bioethanol, C5-C6EtOH = pentose + hexose based bioethanol, C6EtOH = hexose based bioethanol, CHP = combined heat and power, FU = functional unit (1-functional unit (processing of 1-ton collective feedstock, comprising (w/w) 45.2% CWW + 0.9% CB + 53.9% CS), Net GWP = total biorefinery GWP minus total GWP for the equivalent fossil-based products (processes), NWS = total biorefinery water scarcity minus total water scarcity for equivalent fossil-based products (processes).

Table D.4: The considered percentage sub-weightings in the sensitivity analysis

Sustainability sub-metrics	'Case A' baseline	Sc. 1	Sc. 2	Sc. 3	Sc. 4	Sc. 5	Sc. 6	Sc. 7	Sc. 8	Sc. 9	Sc. 10	Sc. 11	Sc. 12	Sc. 13	Sc. 14
Total capital investment, TCI	4.00	13.33	14.00	13.00	13.00	13.33	13.33	13.33	13.33	13.33	13.33	13.33	13.33	13.33	13.33
Total production cost, TPC	4.00	13.33	13.00	14.00	13.00	13.33	13.33	13.33	13.33	13.33	13.33	13.33	13.33	13.33	13.33
Net Present Value, NPV	32.00	13.33	13.00	13.00	14.00	13.33	13.33	13.33	13.33	13.33	13.33	13.33	13.33	13.33	13.33
Net GWP [a]	10.00	5.71	5.71	5.71	5.71	14.00	4.33	4.33	4.33	4.33	4.33	4.33	5.71	5.71	5.71
NWS [b]	10.00	5.71	5.71	5.71	5.71	4.33	14.00	4.33	4.33	4.33	4.33	4.33	5.71	5.71	5.71
Terrestrial acidification	4.00	5.71	5.71	5.71	5.71	4.33	4.33	14.00	4.33	4.33	4.33	4.33	5.71	5.71	5.71
Freshwater eutrophication	4.00	5.71	5.71	5.71	5.71	4.33	4.33	4.33	14.00	4.33	4.33	4.33	5.71	5.71	5.71
Terrestrial ecotoxicity	4.00	5.71	5.71	5.71	5.71	4.33	4.33	4.33	4.33	14.00	4.33	4.33	5.71	5.71	5.71
Freshwater ecotoxicity	4.00	5.71	5.71	5.71	5.71	4.33	4.33	4.33	4.33	4.33	14.00	4.33	5.71	5.71	5.71
Fossil resource scarcity	4.00	5.71	5.71	5.71	5.71	4.33	4.33	4.33	4.33	4.33	4.33	14.00	5.71	5.71	5.71
Job creation (skilled + unskilled labour in biorefinery)	4.00	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	7.00	6.50	6.50
Energy security (net electricity)	6.00	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.50	7.00	6.50
Human toxicity potential	10.00	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.50	6.50	7.00
TOTAL (%)	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

[a] Net GWP = total biorefinery global warming potential (GWP) minus total GWP for the equivalent fossil-based products (processes); [b] NWS = total biorefinery water scarcity minus total water scarcity for equivalent fossil-based products (processes). 'Case A baseline' scenario represents a 40% LCC, 40% eLCA & 20% sLCA weighting perspective, with the sub-weightings depicted; Scenarios 1-14 (Sc.1-14) each represents prioritized weightings for the sub-metric (dominant sub-metric) in the first column of the table. eLCA = environmental life cycle assessment, LCC = life cycle costing, sLCA = social life cycle assessment